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L24: Entry 10 of 25 File: USPT Jun 30, 1998

DOCUMENT-IDENTIFIER: US 5774832 A
TITLE: Inertial navigation with gravity deflection compensation

Abstract Paragraph Left (1):
The novel navigation system, suited for commercial aircraft, includes a sensor for outputting a signal representing a first navigation parameter, a memory having condensed gravity compensation data, and a processor for deriving a second navigational parameter. The processor derives the second navigational parameter from the signal and a subset of the condensed compensation data based on aircraft position. The condensed memory, based on regional gravity deflections, stores sequential gravity compensation values and corresponding navigational coordinates. To conserve memory, adjacent compensation values differ by at least a preset gravity compensation increment. The compensation increment, based on a gravity deflection between 30 and 100 micro-radians, is adequate for commercial aircraft.

Brief Summary Paragraph Right (1):
The present invention concerns the compensation of gravity deflections in navigation systems. It specifically concerns an inertial navigation system having a memory of gravity compensation values for compensating gravity deflections.

Brief Summary Paragraph Right (2):
An inertial navigation system is a self-contained system that uses inertial sensors and a system processor to determine velocity and position of a vehicle. The inertial sensors, which typically include a set of accelerometers on the vehicle, measure linear acceleration of the vehicle. The system processor, usually a digital computer, integrates the acceleration data, according to classical Newtonian mechanics, to estimate velocity and position.

Brief Summary Paragraph Right (3):
These estimates of velocity and position suffer from inherent limits to accuracy. Such limits stem not only from accelerometer bias and misalignment, but also from sensitivity limits inherent to the very nature of accelerometers. Accelerometers suffer particularly from an inability to distinguish vehicle acceleration from gravitational acceleration.

Brief Summary Paragraph Right (4):
Instead of measuring vehicle acceleration, accelerometers measure the sum of vehicle acceleration and gravitational acceleration, or gravitation. The sum is known as specific force acceleration. As a result, determining the actual vehicle acceleration requires accounting for the effect of gravitation on the accelerometers. This accounting entails adding (or subtracting) a gravitation term to the outputs of the accelerometers and proceeding to calculate velocity and position, using the adjusted accelerations.

Brief Summary Paragraph Right (7):
Gravity deflections, measured as North and East angles of deflection from the vertical, typically have magnitudes on the order of ten micro-radians (.mu.rad). Although deflections of this order affect the accuracy of inertial navigation systems, the effect is generally thought negligible, particularly in commercial systems. Recent observations, however, have shown some terrestrial regions having gravity deflections large enough to seriously affect even commercial systems.

Brief Summary Paragraph Right (8):
For example, the 34,000-feet-deep Kuril trench, stretching along the North Pacific airway between the U.S. and the Far East, generates gravity deflections exceeding 300 micro-radians. Deflections of this magnitude drive the velocity and position estimates of conventional inertial navigation systems outside acceptable performance bounds. As a consequence, vehicles using these systems are apt to weave, or oscillate, about their desired courses, wasting time and fuel in the process.

Brief Summary Paragraph Right (9):
To meet these concerns, high-precision navigation systems have implemented various compensation schemes. These have included using statistical estimators to estimate the deflections, gravimeters to measure actual gravitation, and two-dimensional polynomial models to compute the deflections. Although these schemes improve accuracy, they are also quite costly in terms of computational overhead or hardware complexity, especially for the comparatively modest demands of commercial systems. Accordingly, an inertial navigation system with a simple cost-effective mechanism for compensating gravity deflections would advance the art of inertial navigation.

Brief Summary Paragraph Right (10):
The present invention, a navigation system for mounting to a vehicle, comprises an inertial sensor for outputting a sensor signal representing a first navigation parameter of the vehicle, a memory having gravity compensation data for a terrestrial region, and a processor coupled to the inertial sensor and the memory. The processor accesses a subset of the gravity compensation data, based on position of the vehicle, and derives a second navigational parameter, based on the sensor signal and the subset of gravity compensation data.

Drawing Description Paragraph Right (1):
FIG. 1 shows the inertial navigation system of the present invention.

Drawing Description Paragraph Right (3):
FIG. 3 illustrates the method of operation of the inertial navigation system of the present invention.

Detailed Description Paragraph Right (1):
FIG. 1 shows a block diagram of inertial navigation system 10, according to the present invention. Navigation system 10, mounted in an aircraft (not shown), comprises inertial sensors 20, processor 22, compensation memory 24, flight management subsystem 26, and navigational parameter display 28.

Detailed Description Paragraph Right (4):
The present invention, therefore, provides a navigation system with a simple mechanism, i.e., a look-up table, to use in compensating gravity deflections. Moreover, unlike the complex and computationally burdensome prior art schemes, the present system, is particularly suitable for commercial aircraft applications. However, for applications where the size of memory 24 may be problem, memory 24 preferably includes gravity compensation data that is condensed (compressed or abridged), according to the method illustrated in FIG. 2.

Detailed Description Paragraph Right (9):
Step 56 entails quantizing the data, according to a preset least-significant gravity compensation increment and a preset number of bits. For example, the preferred embodiment uses 3 bits for each north and east compensation value, with the least-significant increment based on a deflection between 30 and 100 micro-radians, such as 80 micro-radians. The 30-100 micro-radian range is suitable for the demands of commercial navigation systems.

Detailed Description Paragraph Right (25):
The compensation preferably proceeds at two process rates. The horizontal velocity increments are preferably updated every 5 seconds, using a new position for accessing the compensation memory, etc. This rate is suitable, since the rate of change of gravity deflections is generally much slower than the rate of change of position, i.e., velocity of the aircraft. The final step of adding the velocity increments occurs 50 times a second, the preferred parameter update rate of the navigation system.

Detailed Description Paragraph Right (26):
In sum, the present invention provides a navigation system with a condensed, or compressed, memory of gravity compensation data for compensating navigational parameters. The novel condensed memory enables simple and efficient gravity deflection compensation, without the cost and complexity of prior compensation schemes.

Other Reference Publication (2):
Article "Gravity Compensation For Inertial Navigation Systems Demonstration Program", Administrative Report#1, CDRL Item #19, Prepared by Northrop Corporation, Electronics Division, Nov. 1983.

Other Reference Publication (4):
Article "Self-Contained Real Time Estimation and Compensation of Vertical Deflection in a Precise Marine Inertial Navigator" Author James A. Lowrey III, Glen Y. Oak and Paul F. Zavattero from Rockwell International, Jun. 1984, pp. 165-178 in the Jurnal of the Institute of Navigation, vol. 31, No. 3, Fall 1984.

Other Reference Publication (5):
B.A. Kriegsman et al.; Gravity-Model Errors in Mobile Inertial-Navigation Systems; Journal of Guidance Control and Dynamics; May-Jun. 1986; vol. 9, No. 3; pp. 312-318.

CLAIMS:

1. A navigation system for mounting to a vehicle, the system comprising:

an inertial sensor for sensing a first navigational parameter of the vehicle and outputting a sensor signal representing the first parameter;

a memory having gravity compensation data for a geographic region; and

a processor coupled to the inertial sensor and the memory, the processor including:

means for accessing a subset of the gravity compensation data, based on position of the vehicle; and

means for deriving a second navigational parameter, based on the sensor signal and the subset of gravity compensation data.

6. The system of claim 4

wherein the means for accessing a subset of the gravity compensation data includes means for searching the plurality of sequential latitudes for a set of latitudes corresponding to a latitude of the vehicle; and

wherein the means for deriving the second navigational parameter includes:

means for interpolating a new gravity compensation value from the subset of gravity compensation values; and

means for adding the new gravity compensation value to the first navigational parameter.

13. The system of claim 11 wherein the gravity compensation data includes a plurality of sequential navigation coordinates, each coordinate corresponding to a value of the plurality of sequential gravity compensation values.

16. A method of condensing gravity compensation data for use in a navigation system having a compensation memory, the method comprising:

storing a plurality of sequential gravity compensation values to a first memory, each value having an associated navigational coordinate corresponding to a geographic region;

storing a first gravity compensation value of the plurality to a first location of the

compensation memory;

searching the plurality of values for a nearest different sequential value, the nearest different sequential value differing from the first value by at least a preset gravity compensation increment; and

storing the nearest different sequential value to a second location of the compensation memory.

23. A method of compensating gravity deflection in a navigation system having a sensor for determining a navigational parameter of a vehicle, the method comprising:

storing a plurality of sequential gravity compensation values to a compensation memory, each value having an associated navigational coordinate corresponding to a region of earth;

accessing a subset of the plurality of gravity compensation values, based on position of the vehicle; and

compensating the navigational parameter, based on the subset of gravity compensation data.

24. The method of claim 23

wherein accessing a subset of the gravity compensation values includes searching for gravity compensation values corresponding to regions near the position of the vehicle; and

wherein compensating the navigational parameter includes:

interpolating the subset of the plurality of gravity compensation values to determine a gravity compensation value for the position of the vehicle; and

adding the gravity compensation value to the navigational parameter.

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L18: Entry 27 of 199 File: USPT Apr 16, 2002

DOCUMENT-IDENTIFIER: US 6374190 B2
TITLE: Method for calibrating an angle sensor and navigation system having an angle sensor

Abstract Paragraph Left (1):
A method for calibrating an angle sensor ascertains an output signal for a zero point and measures an associated operating temperature. The output signal and a reference signal stored for the operating temperature are used to form a new reference signal. A navigation system equipped with a temperature sensor for measuring the operating temperature of the angle sensor and with a memory for storing reference signals is also provided. The calibration method and the navigation system substantially eliminate angle sensor measurement errors attributed to temperature influences.

Brief Summary Paragraph Right (1):
The invention relates to a method for calibrating an angle sensor which is affected by the operating temperature and to a navigation system having an angle sensor.

Brief Summary Paragraph Right (2):
Inexpensive gyroscopes used in navigation systems are particularly prone to provide temperature-dependent measurement values. The output signal for a change in an angular position of 0.degree. per time unit (zero point) can be subject to severe fluctuations during a journey on account of the temperature-dependent measurement. The temperature responses of gyroscopes are individual for each respective gyroscope and cannot be defined in a general manner for a particular type of gyroscope.

Brief Summary Paragraph Right (3):
U.S. Pat. No. 5,527,003 discloses a navigation system for aircraft in which the temperature response of a gyroscope is taken into account during a direction measurement. While the aircraft is in an initial orientation on the ground, a set of direction errors is ascertained for the associated temperatures. The direction of the aircraft is then changed and direction errors are ascertained again and are deducted from the initial values in order to obtain temperature-related values. The values are interpolated on the basis of originally set temperature values.

Brief Summary Paragraph Right (5):
From U.S. Pat. No. 5,394,333 it is known to determine separate correction factors for a position which has been determined using a GPS (Global Positioning System) sensor and using composite navigation sensors. The measure used for the correction factor is the distance between the measured position and the corresponding probable position on a digital road map. The system uses either the position ascertained using the GPS sensor or the position ascertained using composite navigation, depending on which of the two values has the lower correction factor. However, the GPS signal may not be available at all locations or may not be available in uncorrupted form. If the direction of motion is measured using an angle sensor which has temperature-related errors, then the measurement accuracy is influenced, sometimes considerably, by the changing operating temperature of the angle sensor.

Brief Summary Paragraph Right (6):
U.S. Pat. No. 5,297,028 discloses measuring and storing the zero point of an angle sensor for a plurality of operating temperatures. The measured values are used to correct the temperature drift of the angle sensor. If a memory location is missing a measured value, two adjacent, stored values are interpolated.

Brief Summary Paragraph Right (7):
It is accordingly an object of the invention to provide a method for calibrating an angle sensor influenced by the operating temperature and a navigation system having such an angle sensor which overcome the above-mentioned disadvantages of the heretofore-known methods and systems of this general type and which take into account a temperature response of the angle sensor on an individual basis.

Brief Summary Paragraph Right (15):
The zero point of a gyroscope (gyro zero point) or rotation rate sensor can be established when there is no motion, for example when a vehicle is at a standstill, or by using measured values from other sensors, for example a GPS receiver and/or differential wheel sensors. In addition to the gyroscope's output signal for the zero point, the operating temperature of the angle sensor is measured indirectly or directly. The output signal for the zero point is stored and assigned to a particular temperature.

Brief Summary Paragraph Right (25):
With the objects of the invention in view there is also provided, a navigation system, including:

Brief Summary Paragraph Right (31):
the processor being configured for determining a position from the first data from the angle sensor and from the second data from the distance sensor;

Brief Summary Paragraph Right (37):
Although the invention is illustrated and described herein as embodied in a method for calibrating an angle sensor and a navigation system having an angle sensor, it is nevertheless not intended to be limited to the details shown, since various modifications and structural changes may be made therein without departing from the spirit of the invention and within the scope and range of equivalents of the claims.

Drawing Description Paragraph Right (1):
FIG. 1 is a block diagram of a navigation system according to the invention having an angle sensor; and

Detailed Description Paragraph Right (1):
Referring now to the figures of the drawings in detail and first, particularly, to FIG. 1 thereof, there is shown a navigation system 1 which is installed in a land vehicle. It has a nonvolatile main memory 11 which is a flash RAM (Random Access Memory).

Detailed Description Paragraph Right (4):
When the navigation equipment is manufactured, a standard reference signal is stored for each of the temperatures contained in the table 111. This standard reference signal may be the same for all the temperatures. The numbers k.sub.i to k.sub.i+n are each set to the value zero.

Detailed Description Paragraph Right (5):
A microprocessor 12 is connected via a system bus to the main memory 11, to a distance meter 13, which is an odometer, to the angle sensor 14 and to an absolute position sensor 15, which is a GPS receiver, and also to a bulk memory 16, which is a CD-ROM (Compact Disc Read-Only Memory) drive.

Detailed Description Paragraph Right (13):
If, on the other hand, there is an additional output signal V.sub.a available, a new reference signal is formed for this measured operating temperature T of 17.1.degree. C., is used to scale the angle sensor and is stored in the main memory. The following text assumes that the GPS receiver has determined that a vehicle travels on a straight road and that the signal V.sub.a measured by the angle sensor is 2.58 volts.

CLAIMS:

7. A navigation system, comprising:

a processor;

an angle sensor connected to said processor for providing first data to said processor;

a distance sensor connected to said processor for providing second data to said processor;

a temperature sensor connected to said processor for measuring an operating temperature of said angle sensor;

a memory connected to said processor and storing a table for providing reference signals as calibration values for a zero point of the angle sensor for a plurality of given operating temperatures;

said processor being configured for determining a position from the first data from said angle sensor and from the second data from said distance sensor;

said processor being configured for generating, for the operating temperature, a reference signal from a first signal stored for a first temperature lower than the operating temperature and from a second signal stored for a second temperature higher than the operating temperature;

said angle sensor providing an output signal for the zero point, the output signal being measured at the operating temperature, said processor being configured for generating a new reference signal for the operating temperature from the reference signal and from the output signal for the zero point;

said processor converting the new reference signal formed for the operating temperature into a third signal for the first temperature and a fourth signal for the second temperature; and

said memory storing the third signal and the fourth signal.

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L24: Entry 14 of 25 File: USPT Nov 1, 1994

DOCUMENT-IDENTIFIER: US 5359889 A
TITLE: Vertical position aided inertial navigation system

Parent Case Paragraph Right (1):
This is a continuation-in-part of U.S. patent application Ser. No. 07/805,544 for "Gravity Aided Inertial Navigation System" filed Dec. 10, 1991, now U.S. Pat. No. 5,339,684, which is incorporated herein by reference.

Brief Summary Paragraph Right (1):
This invention relates to inertial navigational systems. More specifically, it relates to an integration of a conventional three axis Inertial Navigation System (INS)with a gravity map and a height/depth sensor.

Brief Summary Paragraph Right (2):
Inertial navigation systems are basically a triad of accelerometers in combination with a triad of gyroscopes which provide acceleration information in a known coordinate frame to a navigational computer. The computer integrates the accelerations in an appropriate navigation reference frame from appropriate initial conditions to provide continuous measures of velocity, position and instrument frame attitude.

Brief Summary Paragraph Right (3):
The accelerometers measure specific acceleration made up of platform acceleration in linear combination with gravity but since gravity is not perfectly known, an error may develop. This error together with Inertial Navigation System (INS) instrument errors result in navigation solution errors. These navigation errors grow unbounded predominately at or near zero, schuler and siderial frequencies.

Brief Summary Paragraph Right (6):
Although the prior art which integrates a conventional three axis strapdown, partially or fully stabilized INS with a height sensor improves navigation performance, it does not fully exploit navigation system velocity error observability. If this velocity error observability (which is significantly enhanced if a gravity field anomaly map is also integrated) is exploited, these errors can be bounded. The anomalous gravity field map can also be used in a map matching mode to bound position error as well.

Brief Summary Paragraph Right (7):
A primary objective of the invention is to provide an autonomous covert Inertial Navigation System (INS) wherein inertial velocity errors are bounded without external navigation aids or active instrumentation of ground speed.

Brief Summary Paragraph Right (8):
A further objective of the invention is to provide accurate, self contained navigation with bounded position as well as velocity error by integrating a height (depth) sensor and an anomalous gravity field map with conventional inertial navigation instruments and employing map matching position error control.

Brief Summary Paragraph Right (9):
A further objective of this invention is an integration scheme which takes advantage of navigation system velocity error observability wherein east velocity error, through the mechanism of vertical Coriolis acceleration, is manifested in observable height (depth) error.

Brief Summary Paragraph Right (10):
A still further objective of this invention is an integration scheme wherein gravity disturbance vector estimates, based mainly on the anomalous gravity field map, are used to compensate inertial navigation system accelerometer measurements.

Brief Summary Paragraph Right (11):
Integration of a height/depth sensor and an anomalous gravity field map with a conventional inertial navigation system (INS) results in an improved navigation system referred to herein as the Vertical Position Aided Inertial Navigation System or VPAINS. Like the conventional INS, VPAINS is autonomous and covert but additionally it has bounded velocity and position error.

Brief Summary Paragraph Right (12):
The navigation performance improvement of the VPAINS over that of the conventional INS (no gravity map and no height sensor) is attributable to one open loop and two closed loop mechanisms. The gravity map constitutes a consistent set of disturbance vector components and gravity gradients which are accessed at the estimated navigation position. The three disturbance vector components are used to open loop compensate INS accelerometer outputs. After compensating for normal gravity, the resulting improved measure of vehicle acceleration is integrated into vehicle velocity and position.

Brief Summary Paragraph Right (13):
The two closed loop mechanisms for navigation improvement are manifested in the depth sensor (or known sea level) observation comparison with inertially updated vertical position. One of these mechanisms stems from the fact that vehicle acceleration is generally integrated in a local level frame into velocity and position. Since the local level frame is rotating with respect to inertial space, Coriolis acceleration must be compensated for by using navigation system velocity estimates. A vertical Coriolis acceleration error results from an error in the east velocity estimate which is integrated into vertical velocity and vertical position error. The resulting inertially updated vertical position error will be observed with the height/depth sensor.

Detailed Description Paragraph Right (6):
The Vertical Position Aided Inertial Navigation System, VPAINS, [see FIG. 1,] consists of a three axis inertial navigation system (INS), a height or depth sensor, and a stored gravity map, (a memory containing data representing a map of gravity anomalies), all three of which include output ports as illustrated in FIG. 1 by electrical function interconnection lines and output arrow heads. The output data on these function lines, i.e. vertical position data, sensed height data and stored gravity anomalies data respectively is applied via matching input ports signified by the illustrated arrow heads to the optimal filter whose function is to integrate the subsystems to produce the best possible navigation (i.e. provide the best estimates of INS position and velocity and instrumentation parameters). The invention is based on the observation that over time, almost all system errors that impact inertial navigation accuracy manifest themselves in the vertical channel of the navigator. If an independent measure of vertical navigation is available, it can be compared with the INS vertical channel and the difference processed to provide better estimates of the system errors. Different INS configurations (e.g. local - level, space stabilized, strap down) lead to different characterizations of system dynamics. A model of these dynamics is required in applying this invention to a specific configuration. Also open to choice is the type of filter used to process measurements (e.g. Kalman filter, non-linear estimator, least squares estimator). The crucial element is knowledge of how overall system errors manifest themselves in the measurements.

Detailed Description Paragraph Right (7):
Included in the optimal filter is a mechanization of the dynamics of the INS including standard siderial loop, Schuler and vertical channel mechanisms. In this way the propagation of system errors in the navigation channels can be tracked. Of special interest is the dependence of both Coriolis compensation error and vertical gravity estimation error on velocity error. These errors propagate into vertical position error and thus a comparison of INS vertical position with height sensor measurements allows estimation of these INS velocity errors and all other system errors that lead to velocity errors.

Detailed Description Paragraph Right (9):
The standard Kalman gain matrix is then calculated. The gains are applied to the height difference. The results are used to improve the system estimates, and the state uncertainty matrix is updated as is standard in a Kalman filter. This procedure is repeated at a rate mostly dictated by the speed of the computer hardware chosen for a given system. When this system reaches steady state, all navigator errors will be bounded. Other versions of this embodiment result if additional navigation aids such as air speed or water speed sensors are also integrated into the navigation system.

Detailed Description Paragraph Right (10):
Thus a method of inertial navigation is effected where velocity and position error are bounded without external navigation aids or active instrumentation of ground speed by optimally integrating available measurements. This bounding of the velocity and position errors is accomplished by comparing an estimated height (depth) obtained from inertial instruments with an estimate from a height (depth) sensor and combining this with knowledge about the dependence of this difference on system error sources.

CLAIMS:

1. A navigation system, comprising:

a three axis inertial navigation system including an inertial vertical position data output port;

a vertical position sensor including a sensed data output port;

a gravity anomaly map means comprising a memory containing gravity anomalies data and an anomalies data output port; and

an optimal filter including input ports connected to said anomalies data output port, said inertial vertical position data output port and said sensed data output port.

L24: Entry 21 of 25 File: USPT Sep 25, 1984

DOCUMENT-IDENTIFIER: US 4472978 A
TITLE: Stabilized gyrocompass

Abstract Paragraph Left (1):
In a stabilized gyrocompass having meridian seeking gyroscopic means and slaved horizontal gryoscopic means disposed upon a common platform, a signal representative of the angle which develops between the meridian seeking gyro and the platform in response to the dynamic effects of the vehicle is generated. The generated angle is proportional to the northerly inertial velocity term and is used to control the platform in azimuth, thereby providing a dynamically correct stabilized gyrocompass without the use of accelerometers or gravity sensors which are conventional in the art.

Brief Summary Paragraph Right (2):
The invention relates generally to vehicular mounted stabilized gyroscopic instruments and specifically to a gyrocompass that provides both navigation data and stabilization data without the utilization of an accelerometer or separate gravity sensors.

Brief Summary Paragraph Right (4):
Stabilized vehicular mounted gyrocompasses for providing both navigation data and stabilization data are not broadly new and have heretofore been taught, e.g., in U.S. Pat. No. 2,729,108, entitled "Control Systems for Gyroscopic Instruments", issued to Vacquier et al, issued on Jan. 3, 1956 and assigned to the Applicants' assignee. The apparatus disclosed in the Vacquier et al patent includes a pair of gyros of the directional type whose rotors normally spin about horizontal axes. The frames for the respective gyroscopic rotors are independently mounted on a common support. The frames for the rotors are interconnected by a slaving means adapted to maintain the spin axes of the rotors in mutually perpendicular relation. The instrument is provided with azimuthal directivity by gravity responsive means for the meridan gyro of the sensitive element whereby its horizontal spin axis is maintained in a north-south direction due to the effect thereon of the horizontal component of the earth's rotation. The slave gyro of the sensitive element includes a frame supporting a rotor whose horizontal spin axis points in an east-west direction. Both gyros are mounted in neutral equilibrium on a common support. The frames of both gyros are levelled with the spin axes of the rotors thereof in a horizontal plane as by means including electrolytic levels providing limited substantially linear signal outputs with tilt of the frames from a level condition. The support for the gyros includes an azimuth or phantom member with freedom about a vertical axis that is mounted on a platform having freedom relative to the mutually perpendicular pitch and roll axes of the craft. The azimuth member and platform are respectively positioned by an azimuth servomotor and pitch and roll servomotors. The platform and azimuth member are effectively stabilized by a follow-up control from the sensitive element of the gyroscopic instrument which includes the respective servomotors. Azimuth, pitch and roll data transmitters are also operated by the respective servomotors.

Brief Summary Paragraph Right (5):
It is well known to those skilled in the art that in order for a gyrocompass of the type taught in the Vacquier patent to remain continuously pointing north in the presence of vehicular velocity and acceleration, compensation for these dynamic effects must normally be introduced. In the Vacquier patent this compensation is provided by a gravitationally responsive device having an electrolytic liquid which when coupled to an electronic processor means provides a signal representative of the

acceleration of the vehicle in a north-south direction. Improvements in the art have resulted in accelerometers of the type taught in U.S. Pat. No. 2,840,366, entitled "Accelerometers", issued to W. G. Wing, on June 24, 1958, and assigned to the Applicants' assignee. Consequently, it is now conventional within the art to use an accelerometer which senses the northerly acceleration and which then integrates the acceleration signal to provide an inertia north velocity for precessing the meridian or north-seeking gyro about the east axis and for compassing the platform to the north. The compassing signal is ordinarily based upon a comparison between the inertial north velocity term and the northerly component of the vehicle's velocity.

Brief Summary Paragraph Right (7):
A stabilized gyrocompass for providing navigation data and stabilization data is provided without the use of an accelerometer or separate gravity sensors. The apparatus includes first gyroscopic means having a pendulously supported meridian gyro whose spin axis is horizontal and points nominally north and second slaved non-pendulous gyroscopic means whose spin axis is horizontal and points east. The first and second gyroscopic means are mounted on a common platform which is slaved in azimuth via servomechanisms to the second gyroscopic means. The platform, controlled by the second gyroscopic means, does not move in azimuth relative to the first gyroscopic means, while the first gyroscopic means is permitted to move such that an angle results between the platform and the first gyroscopic means. The resulting angle is proportional to the northerly inertial velocity, and thus a signal representative of this northerly inertial velocity may be utilized to precess the first gyroscopic means about the east axis and may also be compared with the vehicular velocity for compassing and damping the platform in azimuth.

Detailed Description Paragraph Right (1):
Referring now to FIG. 1, an illustration of a portion of a stabilized gyrocompass 10 utilizing the present invention is provided. A pair of perpendicular axes delineate north-south directions and east-west directions which are helpful in understanding the orientation of the first gyroscopic means 11 and second gyroscopic means 12, hereinafter described in greater detail. The first gyroscopic means 11 and the second gyroscopic means 12 are supported within a case or fixed gimbal ring 13 which is fixed with respect to the ship or other vehicle within which the stabilized gyrocompass 10 is utilized. A roll gimbal 14 is aligned along a roll gimbal axis which lies along or parallel to the fore-aft axis of the ship and the roll gimbal 14 is journalled to the fixed gimbal 13 to allow rotation of the roll gimbal with respect to the fixed gimbal ring about the fore-aft axis. The pitch gimbal or azimuth platform 15 is journalled within the roll gimbal 14 to allow rotation of the azimuth platform 15 about an axis perpendicular to the fore-aft axis thereby indicating the pitch of the ship. An azimuth gimbal 16 is journalled within the azimuth platform 15 to allow rotation of the azimuth gimbal 16 about an axis perpendicular to the plane of the azimuth platform 15. A first bifurcate extension or first yoke is disposed at one end of the azimuth gimbal 16 and fixedly attached to and supporting a circular frame 20. A second bifurcate extension 24 or second yoke is disposed at the opposite end of the azimuth gimbal 16 and in a plane perpendicular to the plane of the first bifurcate extension 17, and the second bifurcate extension is fixedly attached to and supporting a circular frame 25. The circular frames 20, 25 function as outer gimbals for the first gyroscopic means 11 and the second gyroscopic means 12, respectively.

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L14: Entry 9 of 40 File: USPT Feb 26, 2002

DOCUMENT-IDENTIFIER: US 6351310 B1
TITLE: Reduced minimum configuration interferometric fiber optic gyroscope with simplified signal processing electronics

Brief Summary Paragraph Right (2):
The interferometric fiber optic gyroscope (IFOG) is an established technology for accurately measuring angular rotation. Because the IFOG is an optical, solid state design with no moving parts, it can be used for long life, high reliability applications such as land vehicle navigation.

Brief Summary Paragraph Right (3):
Requirements for a gyroscope intended for use in land navigation systems with coupled dead-reckoning (DR) and GPS (Global Positioning System) input are governed more by cost than by performance considerations. The gyro is used as a gap filler for those systems where no outage is permissible. The GPS data can then be used to periodically correct the dead reckoning sensors, reducing the demands on each. The cost of this type of land navigation system is heavily dependent on the cost of the gyroscope employed. Although the wide performance range of the IFOG makes it well suited for applications such as land navigation, further cost reduction in the gyroscope optical configuration and electronic signal processing is required to make this technology economical to use for many systems such as land navigation systems.

Brief Summary Paragraph Right (6):
In order to reduce the optical configuration complexity and cost, yet maintain the principal of reciprocity, a "reduced minimum configuration" is used. In the reduced minimum configuration (RMC) IFOG, the first coupler has been removed and the interferometer output is read out through a detector positioned at the back facet output of the light source. The light passes through the source before being received by the detector. The RMC gyroscope maintains the principal of optical reciprocity since the light in the interferometer still traverses a common optical path. The inherent system loss of 6 dB from the first coupler is eliminated. Also, depending on the type of light source chosen, and the drive current operating range, the source can act as an optical amplifier for the returning light. Therefore, the signal-to-noise ratio of the RMC gyroscope is as good, and potentially can be better than the conventional MC gyroscope design. Many low cost laser diode packages contain a back facet photo-detector. Thus, the detector is provided by the laser diode manufacturer and the cost of purchasing a separate detector is eliminated in this design. Also, the equipment and labor needed to align the first coupler output fiber to a separate detector is eliminated. The detector is aligned to the back facet by the manufacturer of the laser diode. When the input fiber pigtail is aligned to the optical source, the output is automatically aligned to the detector in the same operation. The RMC also eliminates two fiber-to-fiber fusion splices, further reducing the optical assembly cost.

Detailed Description Paragraph Right (4):
Many low cost semiconductor light source packages contain a back facet photo detector. Thus, the detector is provided by the light source manufacturers. Using this approach, the cost of purchasing a separate detector is eliminated. The detector 25 is aligned with the back facet output 20b by the manufacturer of the light source. When the input fiber pigtail is aligned to the optical source, the output is automatically aligned to the detector in the same operation. This approach also eliminates several fiber splices. Integration of the polarizer onto the coupler combined with pigtailing this

coupler/polarizer assembly onto the light source could further reduce the number of optical splices. Alternatively, it is possible to fabricate all of the required fiber components on a single length of fiber.

Detailed Description Paragraph Right (5):
For most land navigation applications, the input rotation rate range of the vehicle is limited by the speed and turning radius of the vehicle. For example, for high performance cars, a maximum rate range of +/-100.degree./sec is sufficient. Because of this limitation, the sensing coil's Sagnac scale factor can be designed so that this maximum rate range is well within an essentially linear region of the gyroscope output transfer function. The sensing coil is constructed using a short fiber coil length wound on a small diameter bobbin. With this type of construction, the rotation rate can be directly determined from the amplitude of the fundamental signal (F1). Since the phase and frequency of the fundamental signal are well known, the most effective way to determine the amplitude is by synchronous demodulation.

Detailed Description Paragraph Right (11):
This configuration eliminates non-essential optical components and splices from the system, allowing for the construction of a lower cost gyroscope. Using the reduced minimum configuration gyroscope with this simplified signal processing electronics approach produces a very attractive cost-to-performance ratio rotation rate sensor for use in many land vehicle navigation applications, such as applications requiring the use of dead-reckoning sensors coupled to GPS systems. The IFOG signal processing system is simple and low-cost to produce, accurately determines rotation rate of the sensor coil, and maintains a constant scale factor during environmental changes.

Detailed Description Paragraph Right (12):
As shown in FIG. 3, a minimum configuration IFOG, rather than a reduced minimum configuration IFOG can be used with the signal processing electronics described above with reference to FIG. 2. In this embodiment, the source/detector arrangement is replaced by a source 21 and a detector 25, and a first coupler 39 is inserted between the laser and the polarizer. The operation of the rest of the circuit is as described above. Using the minimum configuration gyroscope with this simplified signal processing electronics approach produces a very attractive cost-to-performance angular rate sensor for use in many land vehicle navigation and platform stabilization applications. The IFOG signal processing system is simple and low-cost to produce, accurately determines rotation rate of the sensor coil, and maintains a constant scale factor during environmental changes.

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L14: Entry 30 of 40 File: USPT Sep 1, 1987

DOCUMENT-IDENTIFIER: US 4691385 A
TITLE: Optical communication apparatus for a vehicle

Abstract Paragraph Left (1):
A communication apparatus for controllably bidirectionally transferring information between a vehicle and a docking station advantageously utilizes pulsed radiant energy for effecting the information transfer. A first radiant energy emitting device and a first radiant energy detecting device is located on the vehicle and a second radiant energy emitting device and a second radiant energy detecting device is located on the docking station. A first frequency control device recieves electrical signals from the first radiant energy detecting device, produces pulse control signals having a nominal frequency which is variable within a predetermined frequency range, and controllably delivers the produced pulse control signals at the nominal frequency to the first radiant energy emitting device located on the vehicle. A second frequency control device receives electrical signals from the second radiant energy detecting device, produces pulse control signals having a nominal frequency which is variable within a predetermined frequency range, and controllably delivers the produced pulse control signals at the nominal frequency to the second radiant energy emitting device located on the docking station. The frequency of the produced pulse control signals is automatically adaptively modified in response to receiving the electrical signals.

Brief Summary Paragraph Right (1):
This invention relates generally to an apparatus for communicating between a vehicle and a docking station, and, more particularly, to a communication apparatus for controllably bidirectionally transferring information between a vehicle and a docking station.

Brief Summary Paragraph Right (2):
Various types of unmanned or automatic guided vehicles are under development today. Such vehicles typically maneuver about an industrial facility via some navigation or guidance method, and are used to transport manufacturing items to and from various spaced apart locations or docking stations in the industrial facility. Typically, the docking stations include roller conveyors for loading and unloading cargo from a roller bed on the vehicle.

Brief Summary Paragraph Right (3):
Such vehicles normally carry onboard computer systems which are in communication with a central facility computer. The central computer system directs the overall operation of the vehicle at a supervisory level, while the onboard computer performs local navigation tasks. At the local level, communication between the vehicle and a particular docking station is required to insure proper operation of the load management system.

Brief Summary Paragraph Right (5):
Systems utilizing such optical devices have been proposed for other uses in the past. U.S. Pat. 4,025,791, issued to Lennington on May 24, 1977, teaches an optical interrogator and transponder device suitable for identifying a vehicle as it passes into a controlled area. U.S. Pat. No. 4,398,172, issued to Carroll et al. on Aug. 9, 1983, teaches a similar vehicle monitor apparatus. Other known optical communication systems include remote control units offered to operate with various television receivers.

Brief Summary Paragraph Right (8):
In one aspect of the present invention, a communication apparatus for controllably bidirectionally transferring information between a vehicle and a docking station is provided. The apparatus includes first and second radiant energy emitting devices for producing pulsed radiant energy in response to receiving respective pulse control signals. One of the radiant energy emitting devices is located on the vehicle, and the other on the associated docking station. First and second radiant energy detecting devices produce electrical signals responsive to received radiant energy. Like the radiant energy emitting devices, one of the first and second radiant energy detecting devices is located on the vehicle and the other on a docking station. Each of the vehicle and docking stations has associated with it a frequency control device for receiving electrical signals from the associated radiant energy detecting device, producing pulse control signals having a nominal frequency which is variable within a predetermined frequency range, and controllably delivering the produced pulse control signals at the nominal frequency to the associated radiant energy emitting device, in the absence of receiving any electrical signals from the detecting device. In response to receiving electrical signals from the associated detecting device, the frequency control device modifies the frequency of the respective pulse control signals being delivered to the radiant energy emitting device.

Brief Summary Paragraph Right (9):
The instant invention provides bidirectional communication between a vehicle and an associated docking station, is simple in construction, and low in manufacturing cost. Owing to the relatively small number of components utilized in the instant invention, the likelihood of component failure is substantially reduced from prior known systems.

Detailed Description Paragraph Right (2):
In FIG. 1, a bidirectional communication system is shown which includes apparatus associated with a vehicle 11 and apparatus associated with a corresponding docking station 12. The vehicle apparatus includes a microprocessor 13 connected to a first frequency control means 14 through a first trigger means 16. First radiant energy emitting means 18 and radiant energy detecting means 20 are connected to the first frequency control means 14.

Detailed Description Paragraph Right (4):
Referring next to FIGS. 2 and 3, an embodiment of the instant invention is shown in schematic form. FIG. 2 is a central circuit diagram common to both the vehicle 11 and the docking station 12. In other words, each of the vehicle 11 and the docking station 12 includes a circuit identical to that presented in FIG. 2 to avoid redundancy, only one such circuit is set forth in the drawings. FIG. 3 illustrates circuitry unique to the vehicle 11 and the docking station 12 that connects at indicated points to the circuit of FIG. 2. The following discussion clarifies the relationship between FIGS. 2 and 3.

Detailed Description Paragraph Right (5):
FIG. 2 is described below as it relates to components associated with the vehicle 11. Each element of FIG. 2 has a corresponding element associated with the docking station 12, and identified by the prime of the same element number. The first radiant energy emitting means 18 produces pulsed radiant energy in response to receiving respective pulse control signals. The first radiant energy emitting means 18 includes a light emitting diode 34 connected from supply voltage through a current limiting resistor and a transistor 36 to circuit ground. A second light emitting diode 38 and associated current limiting resistor is connected in parallel with the light emitting diode 34. The input to the transistor 36 is connected through a resistor biasing network and an inverter 40 to a logic gate 42. The logic gate 42 is, for example, a dual input NAND gate. One input terminal of the logic gate 42 is the "trigger" input circuit terminal 44.

Detailed Description Paragraph Right (9):
The above description of FIG. 2 discusses each of the main circuit components of the vehicle communications apparatus shown in the block diagram of FIG. 1. Included in the above discussion is the first frequency control means 14, the first radiant energy emitting means 18, and the first radiant energy detecting means 20. The interconnection of various circuit elements is discussed with respect to each of these

major circuit components. In like manner, the major circuit components of the docking station 12 includes identical counterpart circuit elements to those discussed above. For example, the second radiant energy emitting means 18' associated with the docking station 12 includes a first light emitting diode 34' and a second light emitting diode 38' connected through a transistor 36' in identical manner to the interconnection of the first and second light emitting diodes 34, 38 with the transistor 36 as described with respect to the first radiant energy emitting means 18. Owing to the exact duplication of the vehicle 11 and docking station 12 circuitry, depicted in FIG. 2, further description of the interconnecting elements is omitted.

Detailed Description Paragraph Right (10):
Referring now to FIG. 3, the interconnection of elements unique to the vehicle 11 and the docking station 12 are illustrated. Each of the vehicle 11 and the docking station 12 includes a respective trigger means 16, 26. The vehicle trigger means is simply a logic gate 81 having an input terminal connected through a biasing network to the vehicle computer 13, and having an output terminal connected to the "trigger" input terminal 44. The "receive" output terminal 78 is connected directly to the vehicle computer 13.

Detailed Description Paragraph Right (13):
Operation of the appartus 10 is best described in relation to its use for controllably bidirectionally transferring load management information between a material handling vehicle and an associated docking station. In a typical load transfer arrangement, each of the vehicle 11 and the docking station 12 includes a motorized conveyor adapted to move cargo from place to place. For purposes of the following discussion, it is assumed that the vehicle 11 is positioned in a location relative to the docking station 12 sufficient to allow transfer of cargo between the vehicle conveyor and the stationary docking station conveyor. With the vehicle 11 and the docking station 12 having these relative positions, the communication apparatus located on each of the vehicle 11 and the docking station 12 are aligned for optical communication. In other words, radiant energy emitted from one of the first and second radiant energy emitting means 18, 18' impinges on an opposing one of the first and second radiant energy detecting means 20, 20'.

Detailed Description Paragraph Right (17):
Assuming now that the second radiant energy emitting means 18' located on the docking station 12 begins to pulse at a nominal frequency, for example, 5 Khz, the communications apparatus associated with the vehicle 11 operates in the following manner. The radiant energy pulses from the second radiant energy emitting means 18' are received by the phototransistor 46. Electrical signals representing the radiant energy pulses are passed through the discriminator means 48 and are received by the phase locked loop 58 at the frequency input terminal 60. The first phase comparator 68 delivers the phase difference signal to the voltage controlled oscillator 66 which, in turn, automatically adaptively adjusts the nominal operating output frequency to correspond to the received input frequency. The input and output frequencies are thus brought into synchronization, and the signal delivered from the first phase comparator 68 to the comparator 72 causes the comparator 72 to deliver an enable signal to the monostable multivibrator 74. Consequently, the monostable multivibrator 74 is triggered by the leading edge of the pulse delivered from the second phase comparator 70, and the transistor 76 and light emitting diode 80 are turned "on" by the resulting signal delivered from the monostable multivibrator 74. The resulting "receive" signal is delivered at the "receive" terminal 78.

Detailed Description Paragraph Right (18):
If it is desired that the first radiant energy emitting means 18 located on the vehicle 11 be turned "on", a "transmit" signal is delivered from the vehicle computer 13 to the first trigger means 16. This transmit signal causes the logic gate 81 to deliver a "trigger" signal to the "trigger" input terminal 44 of the logic gate 42. The trigger signal enables the logic gate 42 to pass the pulse control signal from the voltage controlled oscillator through the logic gate 40 to the transistor 36. Responsively, the transistor 36 is pulsed "on" and "off" at the frequency determined by the pulse control signal, and both of the light emitting diodes 34, 38 are correspondingly pulsed "on" and "off". The light emitting diode 38 is again provided for diagnostic purposes, while the light emitting diode 34 delivers radiant energy pulses to the corresponding phototransistor 46' located on the docking station 12.

Detailed Description Paragraph Right (20):
As can be determined from the above description, both of the communication circuits associated with the vehicle 11 and the docking station 12 are adapted to produce a "receive" signal in response to detecting a particular radiant energy frequency signal delivered to an associated radiant energy detecting means 20, 20'. Both circuits are particularly designed to prevent false indications owing to either ambient or spurious radiant energy signals, or to self reflected radiant energy signals.

Detailed Description Paragraph Right (21):
The first trigger means 16, associated with the vehicle 11, is described above. The second trigger means 26, associated with the docking station 12, must be sufficient to produce a "trigger" signal at a logic voltage level in response to a relatively high voltage command signal from the programmable controller 22. Referring to FIG. 3, an AC signal is delivered to the bridge rectifier 82 by the program controller 22. This signal is rectified and delivered to the input of the opto isolator 84, which, in turn, produces a voltage signal that is delivered to the comparator 86. The comparator 86 merely prevents low level signals from inadvertently passing to the communications device, caused, for example, by leakage current in the opto isolator 84. The signal delivered by the comparator 86 is a pulsing signal having a frequency representative of the AC signal applied to the bridge rectifier 82. This pulsing signal is delivered to the monostable multivibrator 90 which supplies the "trigger" signal to the "trigger" input terminal 44' of the communications device located on the docking station 12.

Detailed Description Paragraph Right (23):
As an example of bidirectional communications utilized in the apparatus 10, assume again that the vehicle 11 is positioned in proximity to the docking station 12, and that the vehicle 11 is required to unload cargo from its roller bed to a conveyor at the docking station 12. Upon stopping in position, a handshaking protocol is established. The vehicle 11 turns "on" the first radiant energy emitting means 18, and the programmable controller 22 receives this signal as described above. The docking station 12 then turns "on" the corresponding second radiant energy emitting means 18', which signal is likewise received by the microcomputer 13 of the vehicle 11. Since both the vehicle 11 and the docking station 12 have received signals indicating the presence of the other, the communication link is established and both the microcomputer 13 and programmable controller 22 turn "off" the trigger signals, breaking the communication link and ending the handshake protocol.

Detailed Description Paragraph Right (24):
The one of the vehicle 11 and the docking station 12 having cargo to unload, in this case assumed to be the vehicle 11, again turns "on" the first radiant energy emitting means 18'. The docking station 12 receives the signal from the vehicle 11, responsively turns "on" its motorized conveyor system to accept the load, and then turns "on" its respective second radiant energy emitting means 18' to indicate to the vehicle 11 that it is ready to accept the cargo. The vehicle 11 receives the signal from the docking station 12, and turns "on" its roller bed to transfer the cargo to the docking station conveyor. Upon sensing receipt of the cargo, by various available means such as pressure sensors, proximity detectors, etc., the docking station 12 turns "off" the second radiant energy emitting means 18'. The vehicle 11 acknowledges that the cargo has been received by the docking station 12, and responsively turns "off" the first radiant energy emitting means 18. At this point, the transfer of cargo from the vehicle 11 to the docking station 12 is complete and the vehicle 11 is free to proceed to its next assigned task. Transfer of cargo in the opposite direction, from the docking station 12 to the vehicle 11, is accomplished in exactly the same manner with the order of information transfer being simply reversed from that described above.

Detailed Description Paragraph Right (25):
Therefore, the above described invention advantageously provides a bidirectional communication system for transferring information between a vehicle 11 and a docking station 12, that is simple and low cost to manufacture and maintain. It is rugged for use in an industrial environment and is not subject to interference from ambient conditions.

CLAIMS:

1. Communication apparatus for controllably bidirectionally transferring information between a vehicle and a docking station, comprising:

first and second radiant energy emitting means for producing pulsed radiant energy in response to receiving respective pulse control signals, one of said first and second radiant energy emitting means being located on said vehicle and the other on said docking station;

first and second radiant energy detecting means for producing electrical signals responsive to received radiant energy, one of said first and second radiant energy detecting means being located on said vehicle and the other on said docking station;

first frequency control means for receiving said electrical signals from said one of said first and second radiant energy detecting means located on said vehicle, producing pulse control signals having a nominal frequency which is variable within a predetermined frequency range, controllably delivering said produced pulse control signals at said nominal frequency to said one of said first and second radiant energy emitting means located on said vehicle in the absence of receiving said electrical signals, and automatically adaptively modifying the frequency of said respective produced pulse control signals in response to receiving said electrical signals;

second frequency control means for receiving said electrical signals from said one of said first and second radiant energy detecting means located on said docking station, producing pulse control signals having a nominal frequency which is variable within a predetermined frequency range, controllably delivering said produced pulse control signals at said nominal frequency to said one of said first and second radiant energy emitting means located on said docking station in the absence of receiving said electrical signals, and automatically adaptively modifying the frequency of said respective produced pulse control signals in response to receiving said electrical signals; and

wherein said vehicle includes first trigger means for controllably delivering a transmit trigger signal to said first frequency control means in response to predetermined status conditions of said vehicle, said docking station includes second trigger means for controllably delivering a transmit trigger signal to said second frequency control means in respose to predetermined status conditions of said docking station, and each of said first and second frequency control means include logic means for receiving said respective transmit trigger signal and blocking delivery of said respective pulse control signals to said respective one of said first and second radiant energy emitting means in response to the absence of said transmit trigger signal.

4. Communication apparatus for controllably bidirectionally transferring information between a vehicle and a docking station, each of said vehicle and said docking station having a respective computer associated therewith, comprising:

a first light emitting diode positioned on said vehicle;

a first phototransistor positioned on said vehicle;

a first phase locked loop having a frequency input terminal connected to said first phototransistor, a frequency output terminal connected to said first light emitting diode, and a signal output terminal connected to said vehicle;

a second light emitting diode positioned on said docking station;

a second phototransistor positioned on said docking station;

a second phase locked loop having a frequency input terminal connected to said second phototransistor, a frequency output terminal connected to said second light emitting diode, and a signal output terminal connected to said docking station computer;

a first logic gate serially connected between said first light emitting diode and said

first phase locked loop frequency output terminal and having a trigger input terminal connected to said vehicle computer, and a second logic gate serially connected between said second light emitting diode and said second phase locked loop frequency output terminal and having a trigger input terminal connected to said docking station computer; and

wherein respective ones of said first and second light emitting diodes and said first and second phototransistors are adapted to be in optical alignment with one another in response to said vehicle being positioned at a predetermined location relative to said docking station.

6. Communication apparatus for controllably bidirectionally transferring information between a vehicle and a docking station, comprising:

first and second radiant energy emitting means for producing pulsed radiant energy in response to receiving respective pulse control signals, one of said first and second radiant energy emitting means being located on said vehicle and the other on said docking station;

first and second radiant energy detecting means for producing electrical signals responsive to received radiant energy, one of said first and second radiant energy detecting means being located on said vehicle and the other on said docking station;

first frequency control means for receiving said electrical signals from said one of said first and second radiant energy detecting means located on said vehicle, producing pulse control signals having a nominal frequency which is variable within a predetermined frequency range, controllably delivering said produced pulse control signals at said nominal frequency to said one of said first and second radiant energy emitting means located on said vehicle in the absence of receiving said electrical signals, and automatically adaptively modifying the frequency of said respective produced pulse control signals to be substantially equal to but out of phase with said respective received electrical signals in response to receiving said respective electrical signals;

second frequency control means for receiving said electrical signals from said one of said first and second radiant energy detecting means located on said docking station, producing pulse control signals having a nominal frequency which is variable within a predetermined frequency range, controllably delivering said produced pulse control signals at said nominal frequency to said one of said first and second radiant energy emitting means located on said docking station in the absence of receiving said electrical signals, and automatically adaptively modifying the frequency of said respective produced pulse control signals to be substantially equal to but out of phase with said respective received electrical signals in response to receiving said electrical signals; and

wherein said vehicle includes first trigger means for controllably delivering a transmit trigger signal to said first frequency control means in response to predetermined status conditions of said vehicle, said docking station includes second trigger means for controllably delivering a transmit trigger signal to said second frequency control means in response to predetermined status conditions of said docking station, and each of said first and second frequency control means include logic means for receiving said respective transmit trigger signal and blocking delivery of said respective pulse control signals to said respective one of said first and second radiant energy emitting means in response to the absence of said transmit trigger signal.

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L14: Entry 24 of 40 File: USPT Sep 13, 1994

DOCUMENT-IDENTIFIER: US 5347387 A
TITLE: Self-aligning optical transceiver

Brief Summary Paragraph Right (2):
This invention relates to a compact, self-aligning optical transceiver, and more specifically to a transceiver with optical components suspended in a frictionless manner either electromagnetically or pneumatically and protected from a wide range of relative carrier movement and acceleration.

Brief Summary Paragraph Right (33):
On ground vehicles, transceivers could be used with image recognition logic for collision alert and guidance. In dependent mode, the transceivers could link with other networked transceivers both mobile and fixed for chaining of vehicles, collision avoidance, automated ground traffic control, telephone and data link services.

Brief Summary Paragraph Right (44):
The principal object of this invention is to provide a compact, lightweight, self-aligning, yet economical optical transceiver suitable for secure, high bandwidth duplex communication over dispersion limited beams of light through atmosphere, water or free-space for mobile or stationary applications in a line-of-sight environment. Alternatively, the transceiver is suited for convenient replacement of heavy, difficult to route or unsightly cabling in stationary environments. Another object of the invention is to provide an apparatus suitable for independent mode applications such as laser projection and three dimensional imaging. Another object of the invention is to provide a compact, light weight and efficient system of electromagnetic, optical, electro-optical and electronic components capable of discriminating received radiation from transmitted radiation. Another object of the invention is to provide an electromechanism capable of full surround movement relative to the carrier. Another object of this invention is to provide an easily fabricated low profile motor design which can electromagnetically or pneumatically suspend the armature so as to provide the internal components of the transceiver with excellent isolation from shock, eliminate the need for gimbal rings and precision bearings and also provide a mechanism for accurately measuring force in three degrees of freedom. Another object of the invention is to provide a cooled hermetic environment for the internal components of the invention so as to increase the sensitivity of the electro-optic components, the power handling capability and lifespan of the semiconductor components and also to protect the components from damage, user tampering and the mirror surfaces from oxidation. A further object of the invention is to provide an arrangement of components which provide maximum optical aperture for a given spherical space and also area for control, data relay and inertial navigation electronics.

Brief summary Paragraph Center (11):
Ground Vehicles

Brief Summary Paragraph Type 1 (1):
On aircraft, ground vehicles, terminal buildings, control and approach towers and to relieve radio frequency congestion in terminal areas.

Drawing Description Paragraph Right (9):
FIG. 8 is a plan view of the transceiver which aligns with the optical axis as illustrated. This view best illustrates the outline and sectioning of the object

mirror.

Detailed Description Paragraph Right (1):
The following sections describe a particular embodiment of the Self-Aligning Optical Transceiver, herein referred to as simply the "transceiver". Variations are possible for several functions of the transceiver. Some variations are noted in the following description but this invention is not limited by this description.

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L14: Entry 18 of 40 File: USPT Feb 25, 1997

DOCUMENT-IDENTIFIER: US 5606444 A
TITLE: Wide-angle, high-speed, free-space optical communications system

Brief Summary Paragraph Right (2):
In the last 20 years, computers have played an ever increasing role in the airline industry. For example, computers are used onboard an aircraft for such tasks as aiding navigation, scheduling maintenance, monitoring the operation of equipment as well as for controlling the position of the flight control surfaces to fly the aircraft. On the ground, computers are used to ticket passengers, keep track of luggage, maintain records of seat availability, schedule departure changes, etc. In the past, there has only been a limited exchange of data between the aircraft computer system and the ground-based computer system used by an airline. Such exchange usually took place by hand carrying a floppy disk between the two computer systems.

Brief Summary Paragraph Right (4):
To overcome the problems associated with a fiber optic cable-based communication system, an alternate communications scheme was suggested by the airlines industry. The alternate scheme involved the use of a free-space optical communications system that could transmit information between the aircraft computer system and the ground-based computer system using a modulated infrared light beam. The free-space optical communications system would eliminate the need for the fiber optic cable possible damage from the aircraft pulling away and disconnecting the cable. However, current free-space optical communications systems suffer from at least three problems that, in combination, prevent such communications systems from being readily usable in an aircraft to ground-based computer communication link. First, current free-space optical communications systems do not operate at the high data rate that the airlines are requiring for a commercially viable communication system. For example, the Aeronautical Radio Incorporated (ARINC) standards group is currently developing a communications protocol that requires data communication between an aircraft and a ground-based computer system be accomplished at speeds of 100 Mbits/sec. Second, current state of the art high-speed, free-space optical communications systems often have a narrow field of view and, as such, require additional control systems to align the optical transceivers to ensure proper data transmission. Including such control systems into a free-space optical communications system adds significantly to the cost of the system, as well as introduces a likely source of system failure. Finally, current free-space optical communications systems will not operate in all types of weather conditions experienced at an airport.

Brief Summary Paragraph Right (5):
Therefore, a need exists for a free-space optical communications system that can transmit data between an aircraft and a ground-based system at high speeds over all weather conditions. Additionally, the communication system should have a wide field of view to eliminate the need for any control systems to align the optical components of the system.

Detailed Description Paragraph Right (2):
FIG. 1 shows an aircraft 10 parked near a passenger loading bridge 20. As will be further described below, the free-space optical communications system 30 according to the present invention allows data to be transmitted using infrared light beams that are transmitted between an optical transceiver located behind an infrared window disposed in the side of the aircraft and a corresponding optical transceiver located underneath a passenger loading bridge 20. The transceiver disposed on the underside of

the passenger loading bridge 20 is coupled to the ground-based computer system via a communications cable 40 such as a fiber optic cable. An optional optical shroud 34 may be mounted on the underside of the passenger loading bridge 20. The free-space optical communications system can transmit data between the aircraft computer system (not shown) and the ground-based computer system (also not shown) at a rate of 100 Mbits/sec. Additionally, as will be further described below, the free-space optical communications system according to the present invention has wide transmission beams and corresponding wide fields of view to compensate for misalignments between the aircraft 10 and the passenger loading bridge 20, and needs no active control mechanisms to align the optical transceivers.

Detailed Description Paragraph Right (21):
As will be appreciated, the communication system according to the present invention is "passive" in the sense that no special equipment is needed to align the optical transceivers. This has the benefit of not only being cheaper to manufacture but is also less likely to malfunction as the communication system is exposed to the environment.

Other Reference Publication (6):
H. Kamimura et al., "Radiated Optical Communication System for Mobile Robots," Proceedings of the 4th International Conference on Automated Guided Vehicle Systems: AGVS-4, Jun. 1986, pp. 1372-1381.

Other Reference Publication (15):
S. E. Shladover, "Automatic Vehicle Control Developments in the PATH Program," IEEE Transactions on Vehicular Technology, vol. 40, No. 1, Feb. 1991, pp. 114-130.

L9: Entry 20 of 47 File: USPT May 23, 1995

DOCUMENT-IDENTIFIER: US 5416976 A
TITLE: Gyro compass

Abstract Paragraph Left (1):
A gyro compass having a gyro case housing therein a gyro and supported with freedom of three axes, functions for outputting a signal corresponding to an inclined angle of the gyro spin axis relative to the horizontal plane, and a function for applying a torque around a vertical axis of the gyro case in proportion to an input signal. A controller is supplied with a signal corresponding to the inclined angle and a latitude value at which the gyro compass is located, and a constant relative to the input latitude value is determined by the controller after the gyro compass is energized. A signal, resulting from differentiating the signal corresponding to the inclined angle during a predetermined time, is added to the product of the signal corresponding to the inclined angle and the constant. This added signal functions as the input signal for the gyro, whereby a constant optimum north-seeking movement is carried out regardless of the change of the latitude value. An error corrector is provided having supplied to it the signal corresponding to the inclined angle, the speed signal of the vehicle and its heading azimuth signal, ~~and a~~ bias error caused by the inclined angle of the gyro compass spin axis and an azimuth error caused by the movement of the vehicle are estimated and calculated to thereby reduce an azimuth error caused by any bias error and the vehicles' movement.

Brief Summary Paragraph Right (6):
According to the above-mentioned arrangement, the weight of the gyro case 1 is not applied to the ball bearings 4, 4' of the vertical shafts 2, 2' as a thrust load but is fully received by the suspension wire 5, thereby friction torque of the above-mentioned ball bearings 4, 4' being reduced considerably. A pair of liquid ballistics 6 are mounted on the east and west of the vertical ring 3 in order to apply a north-seeking torque to the gyro.

Brief Summary Paragraph Right (8):
Referring to FIG. 1, it will be seen that a damping weight 7 is mounted on the west side of the gyro case 1 in order to damp the north-seeking movement. As shown in FIG. 1, a primary coil 8-1 of a differential transformer for detecting a declination between the gyro case 1 and the vertical shafts 2, 2' of the vertical ring 3 is attached to the east side of the gyro case 1, and a secondary coil 8-2 of the differential transformer is attached to the opposed position of the vertical ring 3, thereby constituting a follow-up pickup 8. The vertical ring 3 includes a pair of horizontal shafts 9, 9' protruded outwardly from the east and west positions perpendicular to both of the vertical shafts 2, 2' and a gyro spin axis. These horizontal shafts 9, 9' are respectively fitted into inner rings of ball bearings 11, 11' attached to the corresponding positions of a horizontal ring 10 provided outside of the vertical ring 3. The horizontal ring 10 has a pair of gimbal shafts 12, 12' disposed at its positions within the horizontal plane and which are perpendicular to the horizontal shafts 9, 9'. These gimbal shafts 12, 12' are respectively fitted into a pair of gimbal shaft ball bearings 14, 14' attached to a follow-up ring 13 disposed outside of the horizontal ring 10.

Brief Summary Paragraph Right (13):
Owing to the action of the azimuth servo system, the horizontal shafts 9, 9' and the gyro spin axis are constantly kept in an orthogonal relation and the gyro can be prevented from being applied with twisting torque. That is, owing to the actions of

the three shafts such as the vertical shafts 2, 2', the horizontal shafts 9, 9' and the gimbal shafts 12, 12' having the servo system, the gyro case 1 is completely isolated from the angular motion of the ship, thereby the gyroscope being constructed.

Brief Summary Paragraph Right (14):
The above-mentioned liquid ballistics 6 are adapted to give the gyroscope the north-seeking force, i.e., function as the compass.

Brief Summary Paragraph Right (15):
The principle of the liquid ballistic 6 will be described with reference to FIG. 2. FIG. 2 shows the case such that the north-seeking end of the gyro is inclined from the horizontal plane by an anlge .theta.. In this case, assuming that the ship is in its stopped condition, then the liquid surface of the liquid 6-2 becomes perpendicular to the direction of gravity force g. Therefore, as compared with the case such that the inclination of the north-seeking end relative to the horizontal plane is zero, the liquid at the hatched portion of FIG. 2 is decreased in the north-side reservoir 6-1' and is increased in the south-side reservoir 6-1. Assuming now that r.sub.1 is a distance from the horizontal shafts 9, 9' to the center of the two reservoirs 6-1, 6-1', S is a cross section area of the two reservoirs 6-1, 6-1' and .rho. is a specific gravity of the liquid 6-2, then the weight of the liquid at the inclined portion is expressed as:

Brief Summary Paragraph Right (16):
Since the above-mentioned weight unbalance occurs in the two south and north reservoirs 6-1, 6-1' and the moment arm from the horizontal shafts 9, 9' is r.sub.1, a torque T.sub.H produced about the horizontal shafts 9, 9' by the liquid ballistics 6 when the north-seeking end of the gyro is inclined from the horizontal plane by .theta. is approximately calculated as:

Brief Summary Paragraph Right (17):
As described above, we have considered so far the case that the ship is in the still condition. In this case, assuming that .alpha..sub.N is a south-north component of ship's acceleration due to increase and decrease of ship's speed, ship's turning or the like, a torque T.sub.H1 generated from the liquid ballistic 6 under the ship's sailing condition is expressed by the following equation: ##EQU1## As shown in FIG. 3, the damping weight 7 is attached to the gyro case 1 with a distance r.sub.2 (in the direction perpendicular to the sheet of drawing) from the vertical shafts 2, 2' within the plane including the vertical shafts 2, 2' and perpendicular to the gyro spin axis. FIG. 3 shows the gyro case 1 under the condition such that the north-seeking side of the gyro is inclined upward from the horizontal plane by the angle .theta. as viewing from the west. As shown in FIG. 3, a gravitational acceleration g acts on the damping weight 7 of mass m so that a force of m.times.g acts on the damping weight 7 in the Vertical direction. In this case, let us consider that this force is divided into a component m g cos .theta. parallel to the vertical shafts 2, 2' and a component m g sin .theta. parallel to the spin axis. The component m g cos .theta. parallel to the vertical shafts 2, 2' acts only as a load on the vertical shaft ball bearings 4, 4', while the component m g sin .theta. parallel to the spin axis acts on the gyro as a torque multiplied with a distance r.sub.2 from the vertical shafts 2, 2' around the vertical shafts 2, 2'. Assuming that T.phi. represents the above torque, then the torque T.phi. is approximately given by the following equation:

Brief Summary Paragraph Right (18):
That is, the damping weight 7 can be regarded as the apparatus which applies the vertical axes 2, 2' of the gyro with the torque proportional to the inclination of the gyro spin axis relative to the horizontal plane, and the north-seeking motion of the compass can be damped by the damping weight 7.

Brief Summary Paragraph Right (20):
FIG. 4 shows in block form a principle of the conventional gyro compass of FIG. 1, that is, the north-seeking motion of the conventional gyro compass in which an azimuthal error .phi. and an inclined angle .theta. from the due north of the north-seeking end of the gyro spin axis are assumed to be variables and which copes with their initial errors .phi..sub.O, .theta..sub.O are expressed by Laplace operator and transfer function in a block form. In FIG. 4, .OMEGA. represents earth rotation

angular velocity, H angular momentum of gyro, .lambda. latitude of that spot, K north-seeking constant (ballistic constant), .mu. damping constant and S Laplace operator.

Brief Summary Paragraph Right (21):
If now there is the azimuthal error .phi., then a component in which the azimuthal error .phi. is multiplied with a horizontal component .OMEGA. cos .lambda. 100 of the earth rotation velocity .OMEGA. acts on an element 101 around the horizontal axis of the gyro as an angular velocity input, thereby generating the gyro angle .theta. together with an initial inclined angle .theta..sub.O. The vertical ring 3 is similarly inclined by the inclination angle .theta. of the gyro spin axis, and the liquid ballistic 6 attached to the vertical ring 3 is also inclined, thereby the liquid 6-2 within the liquid ballistic 6 being moved in the lower reservoir, thereby a torque K.theta. being generated around the horizontal shaft of the gyro. This torque K.theta. is divided by the angular momentum H of the gyro and is then added with a vertical component .OMEGA. sin .lambda. of the earth rotation angular velocity, thereby being generated as an angular velocity input. This angular velocity input acts on a vertical shaft element 102 of the gyro, and this angular velocity input is added with the initial azimuth error .phi..sub.O to produce the azimuth error .phi., thereby closing the loop. This loop is what might be called a north-seeking loop of the gyro compass. Since two poles expressed by 1/S exist within this loop, this loop becomes an oscillating solution. On the other hand, a torque .mu..theta. is obtaibed by multiplying the gyro inclined angle .theta. with the damping constant .mu. and this torque .mu..theta. is divided by the angular momentum H so as to provide an angular velocity input. This angular velocity input is negatively fed back to the horizontal element 101 of the gyro so as to decrease the above inclined angle .theta., thereby the north-seeking motion of the north-seeking loop being damped. This latter loop is a damping loop.

Brief Summary Paragraph Right (22):
In order to prevent an acceleration error from being caused in the gyro compass due to horizontal accelerations, such as increase and decrease of speed, turning or the like of the ship, the marine gyro compass is generally designed such that the north-seeking motion cycle is selected to be about 90 minutes (Schuler's condition). For this reason, it takes plenty of time for the gyro compass to be settled to the true north so as to be operable since the gyro compass has been energized. This time is what might be called a settle time.

Brief Summary Paragraph Right (23):
In the ordinary ships, the above settle time does not raise a problem in their navigation substantially, however, this long settle time raises a problem in the ships for some special use.

Brief Summary Paragraph Right (26):
In the gyro compass having the above fast settle apparatus, if the latitude at which the gyro compass is located is changed, e.g., at a high latitude if the gyro compass is settled by operating the fast settle apparatus, then the above-mentioned north-seeking motion is placed in the so-called over-damping state due to the action of the torque generated around the vertical axis of the gyro by the damping constant .mu. of the damping loop. As a consequence, the settle time is increased so that, even if the gyro compass is provided with the fast settle apparatus, the settle time cannot be reduced in the high latitude as expected.

Brief Summary Paragraph Right (27):
Further, in FIG. 5 which shows a schematic block diagram of the gyro compass according to the prior art, g represents the gravitational acceleration, R the earth radius, .OMEGA. the rotation angular velocity of earth, H the angular momentum of gyro, .lambda. the latitude at that spot, T.sub.O the time constant provided when the movement of the liquid surface of the ballistic 6 is approximated by the primary delay, K the north-seeking constant, .mu. the damping constant, .alpha..sub.N the acceleration acting on the north-south direction of the gyro case due to the ship's movement, V.sub.NS the north-south velocity of the ship and S the Laplace operator.

Brief Summary Paragraph Right (29):
A precessional angular velocity ##EQU3## provided by multiplying .xi. with a value K/H

(51), which results from dividing the north-seeking constant K by the angular momentum H of the gyro and which is generated around the vertical axis acts around the vertical axis of the gyro case 52 together with the vertical component .OMEGA. sin .lambda. of the earth rotation angular velocity .OMEGA. to produce the azimuthal movement around the vertical axis. Then, the azimuth error .phi. is generated. A value, which results from multiplying the azimuthal error .phi. with the horizontal component .OMEGA. cos .lambda. 53 of the earth rotation angular velocity .OMEGA., is input to a gyro element 54 around the horizontal axis of the gyro as the angular velocity input to thereby generate the gyro inclined angle .theta..

Brief Summary Paragraph Right (30):
The above-mentioned portion is what might be called a north-seeking loop of the gyro compass, in which two poles expressed by 1/S exist within the loop, thereby generating the oscillation solution.

Brief Summary Paragraph Right (31):
An angular velocity ##EQU4## which results from dividing by the gyro angular momentum H the torque ##EQU5## around the vertical axis in which ##EQU6## which results adding the gyro inclined angle .theta. with ##EQU7## is multiplied with the damping constant .mu. is input to a gyro element 54 around the horizontal axis together with the equivalent angular velocity V.sub.NS /R which results from dividing the north-south speed V.sub.NS of ship by the earth radius R, whereby the gyro inclined angle .theta. is reduced and the north-seeking movement is damped. Therefore, this loop is called a damping loop.

Brief Summary Paragraph Right (32):
For the north-seeking loop, the north-south velocity V.sub.NS generates an azimuth error .phi..sub.V proportional to second of the latitude expressed by the following equation. ##EQU8## where C is the azimuth angle of the ship's heading.

Brief Summary Paragraph Right (34):
An azimuth change .phi..sub.B generated by the acceleration between the time t.sub.1 and the time t.sub.2 is called as ballistic amount. A design method for making the azimuth change .phi..sub.B equal to the difference between the velocity errors before and after the acceleration acts is the important condition called the Schuler tuning in the gyro compass and corrects the influence of the acceleration in the form of velocity error (the north-seeking cycle of the gyro compass is extended to 1 to 1.5 hours due to this condition). That is,

Brief Summary Paragraph Right (36):
Instead of the above-mentioned damping weight 7, there is proposed a method in which the north-seeking movement of the gyro compass is carried out by, for example, the inclinometer or tilt meter for outputting the inclined angle of the spin axis of the gyro compass relative to the horizontal plane, an amplifier supplied with the output of the tilt meter, a torquer supplied with the output of the amplifer and so on. This method has the advantage such that the damping characteristic of the north-seeking movement can be arbitrarily corrected only by adjusting the gain of the amplifier.

Brief Summary Paragraph Right (43):
As a first aspect of the present invention, a gyro compass having a gyro case housing therein a gyro whose spin axis is held substantially in the horizontal plane, a supporting device for supporting the gyro case with freedom of three axes, a function for outputting a signal corresponding to an inclined angle of the gyro spin axis relative to the horizontal plane and a function for applying a torque around a vertical axis of the gyro case in proportion to an input signal is comprised of a control apparatus supplied with the signal corresponding to the inclined angle and a latitude value at which the gyro compass is located, wherein a constant (or a damping constant) relative to the input latitude value is set by the control apparatus after the gyro compass is energized, a signal, which results from differentiating the signal corresponding to the inclined angle during a predetermined time, is added to a signal which results from multiplying the signal corresponding to the inclined angle with the constant and an added result is set as the input signal, whereby a constant optimum north-seeking movement is carried out regardless of the change of the latitude value to thereby reduce a settle time.

Brief Summary Paragraph Right (44):
In accordance with a second aspect of the present invention, a gyro compass having a gyro case housing therein a gyro whose spin axis is held substantially in the horizontal plane, a supporting device for supporting the gyro case with freedom of three axes, a function for outputting a signal corresponding to an inclined angle of the gyro spin axis relative to the horizontal plane, a function for applying a torque around a vertical axis of the gyro case in proportion to an input signal and an azimuth transmitter for transmitting an azimuth of the spin axis relative to a navigation vehicle is comprised of an error correcting apparatus supplied with the signal corresponding to the inclined angle, a speed signal of the navigation vehicle and a ship's heading azimuth signal thereof, wherein a bias error caused by the inclined angle of the gyro compass spin axis relative to the horizontal plane and an azimuth error caused by the movement of the navigation vehicle are estimated and calculated to thereby reduce an azimuth error caused by the bias error.

Brief Summary Paragraph Left (1):
where K is the ballistic constant. That is, the liquid ballistics 6 act to apply the torque proportional to the inclination relative to the horizontal plane of the gyro spin axis to the surrounding of the horizontal shafts 9, 9' of the gyro, thereby rendering the north-seeking force to the gyro. Thus, the gyro is rendered the gyro compass'.

Drawing Description Paragraph Right (6):
FIG. 6 is a graph to which references will be made in explaining a gyro compass error caused when a navigation vehicle is moved;

Detailed Description Paragraph Right (6):
Referring to FIG. 7, it will be seen that the control apparatus 52 is comprised of a timer apparatus 62, a switch 61 controlled by the timer apparatus 62, a control amplifier 60 for generating a damping signal for effecting the fast settle, and a constant setting unit 63 for setting a damping constant. The switch 61 is turned on and off by the mode change-over signal from the timer apparatus 62 so that the output signal 51A is controlled. The timer apparatus 62 is energized by a switch-on signal SWA of the gyro compass or by a signal equivalent to the switch-on signal SWA and generates a signal for turning off the switch 61 after a predetermined fast-settle time is passed. A period during the timer apparatus 62 is operated is called a fast-settle mode (a period after this fast-settle mode is called a navigation mode).

Detailed Description Paragraph Right (8):
In the control apparatus 52, during the fast settle mode, a constant relative to the initial input latitude value .lambda. is set by the constant setting device 63. This constant is equivalent to a constant of the conventional damping weight and will hereinafter be determined as a damping constant .mu.'. By the action of the damping constant .mu.', a mechanical damping action of the north-seeking movement done by the conventional damping weight is effected electrically. The damping constant .mu.' thus determined is set to .mu.' in the control amplifier 60.

Detailed Description Paragraph Right (9):
In the above-mentioned constant setting device 63, the damping constant .mu.' relative to the latitude value .lambda. is expressed by the following equation: ##EQU9## where .mu. and cos .lambda..sub.O represent constants by which the north-seeking movement is optimized.

Detailed Description Paragraph Right (12):
In this example, the control amplifier 60 has a differentiation function and a multiplication (or proportion) function, and positively feeds the torque proportional to the differentiated time of the inclined angle of the gyro spin axis (i.e., the output signal 50A of the tilt meter 50) back to the vertical torquer 51 by the former function thereof. More specifically, when the gyro spin axis (e.g., the north-seeking end) is moved upwards, then its ascending speed is increased more. Conversely, when the gyro spin axis is moved downwards, then its descending speed is increased, thereby the cycle of the north-seeking movement being reduced. Further, the control amplifier 60 performs, by the latter function thereof, the electrical damping action instead of the mechanical damping action done by the conventional damping weight so that the optimum constant north-seeking movement is carried out for the change of the latitude,

thus making it possible to reduce the settle time considerably.

Detailed Description Paragraph Right (16):
As a consequence, by the addition of the fast-settle mode shown by .eta., the fast-settle mode .eta. acts to reduce the angular momentum H of the gyro. From the above equation, the north-seeking movement proper cycle Tn of the gyro is expressed as: ##EQU11## Also, a half-period attenuation factor F which expresses the damping degree is expressed as: ##EQU12## It is clear from the above-mentioned equation that the half-period attenuation factor F is constant relative to the latitude value .lambda. at which the gyro compass is disposed. That is, the half-period attenuation factor F is constant relative to any latitude values.

Detailed Description Paragraph Right (18):
If .mu..sub.O represents a proper damping constant, then it is to be understood that the value of the half-period damping factor F can always be made constant relative to the latitude value .lambda.. Therefore, if .mu..sub.O is selected so as to effect the optimum north-seeking operation, then the optimum half-period attenuation factor F can be obtained, which can as a result considerably reduce the settle time of the conventional gyro compass.

Detailed Description Paragraph Right (19):
Incidentally, as clear from the above-mentioned equation, in order to maintain the north-seeking movement stable, the following inequality must be established:

Detailed Description Paragraph Right (21):
While the present invention is applied to the gyro compass which includes neither the tilt meter nor vertical torquer shown in FIG. 1 as described above, the present invention is not limited thereto and may be applied to a gyro compass having, for example, a tilt meter function, that is, the function in which a signal corresponding to an inclined angle of the spin axis relative to the horizon and a torque to the input signal is applied around the vertical axis of the gyro and the function in which a damping gain can be corrected by the latitude value. In this case, if the gyro compass has the above-mentioned functions, then such functions are utilized, that is, without newly providing the tilt meter and the vertical torquer, the control apparatus of the present invention is additionally provided, and then it is possible to obtain the gyro compass in which the optimum north-seeking movement is effected regardless of the change of the latitude value to thereby reduce the settle time.

Detailed Description Paragraph Right (22):
According to the present invention, by adding the fast-settle apparatus of the above configuraton, it is possible to obtain the gyro compass of simplified arrangement which can be made inexpensive and whose settle time is short regardless of the change of the latitude. Although the settle time is increased with the increase of the latitude value in the prior art, according to the present invention, the settle time can be prevented from being increased with the increase of the latitude value so that the settle time can be reduced really. At that time, if the signal corresponding to the time differentiation of the gyro spin axis is applied as the torque around the vertical axis, then the short settle time can be achieved by the simple calculation. Further, as compared with the conventional method in which the north-seeking torque (around the horizontal axis) is increased, according to the present invention (the torque around the vertical axis according to the system of the present invention), the torque necessary for the fast settle operation may be small so that the torquer may be small in size or that the amplifier of small power consumption may be utilized.

Detailed Description Paragraph Right (29):
For simplicity, the azimuthal error .phi. produced at the timing point after sufficient settle time is expressed by the following equation from FIG. 1: ##EQU14## where .mu. is the damping constant which can be described by the relation of the equation (1), .OMEGA. the rotational angular velocity of the earth, .lambda. the latitude of the position at which the gyro compass is located, K the north-seeking gain, ME the error angle at which an inclined angle detecting apparatus is attached to the horizon of the spin axis, AB the term expressed by the sum of drift items changed by a fixed bias proper to the inclined angle detecting apparatus, a temperature or the like, T.sub..theta. the mechanical umbalance torque amount around the horizontal axis, V.sub.NS the velocity of navigation vehicle in the north-to-south axis direction with

its north direction as +, and R the radius of the earth.

Detailed Description Paragraph Right (31):
As described above, due to the fixed bias of the tilt meter 61 which is the inclined angle detecting apparatus for the gyro spin axis, the term AB expressed by the sum of drifts changed with the temperature or the like and the north-south axis velocity of the navigation vehicle, the azimuthal error of the gyro compass A takes place.

Detailed Description Paragraph Right (32):
As shown in FIG. 9, the error correcting apparatus 100 of the present invention is supplied with the inclined angle signal from the gyro compass, that is, a detected inclined signal SA derived from the tilt meter 61, an azimuth signal A.sub.Z, a velocity signal V' of the navigation vehicle having the gyro compass or the like. The error correcting apparatus 100 derives a correcting signal A1 for correcting a bias error caused by the inclined angle signal of the gyro compass and an actual azimuth signal Azt from which an error caused by the movement of the navigation vehicle is removed.

Detailed Description Paragraph Right (37):
In the external information processing unit 100A3 of the error calculating unit 100A, values V'ns and V'ns necessary for presenting the same situation as the situation in which the gyro compass is affected by the movement of the navigation vehicle are calculated by the north-south velocity calculating unit 105 and the differentiator 106.

Detailed Description Paragraph Right (47):
By these correcting amounts .epsilon..theta., .epsilon..phi. and .epsilon.b, the respective estimated amounts of the model calculating unit 100A1 are corrected and the gyro compass detection inclined signal SA and the equivalent inclined signal SB estimated amount from the model calculating unit 100A1 are again compared with each other by the error detecting unit 100A2 for the model calculating unit 100A1. This comparison is continued until the inclined signal estimated value becomes coincident with the inclined signal. At that time, in order to supply the model calculating unit 100A1 with the influence substantially equal to those of the north-south axis direction velocity Vns and the north-south axis acceleration V'ns acting on the gyro compass when the navigation vehicle is moved, the signals V'ns and V'ns from the external information processing unit 100A3 which is supplied with the velocity signal V' and the azimuth signal Az are caused to act on the model calculating unit 100A1.

Detailed Description Paragraph Right (53):
Furthermore, according to the error correcting apparatus of the present invention, in the damping operation done by the inclined angle .theta. of the gyro compass, the signal effects to separate the north-seeking movement of the gyro compass and the signal for causing the azimuthal error from each other and only the signal for causing the azimuthal error is removed to thereby extract the azimuthal error caused by the bias component. Also, the error caused by the acceleration accompanying with the movement of the navigation vehicle can be removed from the azimuth signal. In addition, .phi. can be estimated during a short period of time by adjusting the gains K.theta., K.phi. and Kb in the error detecting unit of the model calculating unit 100A1. Thus, the error correcting apparatus of the present invention can be utilized as the fast-settle apparatus.

CLAIMS:

1. A gyro compass system for navigable vehicles comprising a casing; a gyro mounted in said casing having a spin axis adapted to be normally held substantially in a horizontal plane; means supporting said casing for free movement in three axes; means for producing a signal corresponding to the angle of inclination of said spin axis to said horizontal plane; means for producing a signal corresponding to the azimuth heading of said vehicle; means for producing a signal corresponding to the speed of said vehicle and means for applying a torque about the vertical one of the three axes to modify the movement of said casing; said means for modifying the movement of said casing comprising means responsive to the signal corresponding to said inclined angle of said spin axis, said signal corresponding to the speed of the movement of said vehicle and the signal corresponding to the azimuth heading of said vehicle for

calculating a biasing error caused by an error in the signal corresponding to the angle of inclination of said spin axis relative to the horizontal plane and an error in the azimuth signal relative to the movement of said vehicle; means for providing a correction signal for reducing the error in the azimuth heading and means for applying said correction signal to the means for modifying the movement of said casing.

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Abstract Paragraph Left (1):
The invention relates particularly to sensing devices and techniques which may be used to provide measurement data to aid an inertial navigation system, or attitude and heading reference system, and so bound the growth of errors which increase with time in such systems when operating autonomously. In one aspect, the invention relates to a method of determining the path length along a borehole from a known reference point to a probe or tool which progresses through a drillpipe or tubular string, to provide data to aid an inertial navigation system. A sensing device 15 is used to detect joints 11 between sections of drillpipe or tubular string within the borehole and the path length is determined from the number of joints detected and a known length of each section of drillpipe or tubular string. In another aspect, a flow measuring device, such as an impeller, is used to measure the velocity of the probe or tool through the drillpipe or tubular string. In another aspect the invention relates to a method of determining the velocity of a probe or a tool moving through a drillpipe or tubular string to provide data to aid an inertial navigation system. Two sensing devices, which are spaced apart by a known distance on the probe or tool, are used to detect one or more positions within a drillpipe or tubular string, and the velocity of the probe or tool is determined from the elapsed time between each sensor detection of the or each position and the distance between the sensors.

Brief Summary Paragraph Right (1):
This invention relates to improvements in or relating to methods and apparatus for the precise and continuous determination of the trajectory of underground boreholes using aided inertial navigation systems. The invention relates more particularly to sensing devices and techniques which may be used to provide measurement data to aid an inertial navigation system, or attitude and heading reference system, and so bound the growth of errors which increase with time in such systems when operating autonomously.

Brief Summary Paragraph Right (2):
Most of the directional borehole survey systems currently used for geological survey, mining and the drilling of oil and gas wells derive the path or trajectory of a borehole by determining its inclination and azimuth ~~angles with~~ respect to a prescribed co-ordinate reference frame, ~~often~~ defined by the local vertical and the direction of a north reference, at intervals along the borehole. For instance, inclination may be defined using measurements provided by accelerometers whilst azimuth may be determined using a north seeking gyroscope installed in a probe or tool which can be lowered or raised in the hole on the end of a cable or conductor wireline. The angular information is then combined with measurements of the distance moved along the borehole, such information being derived by measuring the length of the cable extending into the hole. Cable length may be correlated with magnetic marks encrypted on the armour of the cable at known intervals along its length. The measurements of inclination, azimuth and ~~cable length~~ obtained at each location are then processed to obtain estimates of position with respect to the chosen reference frame (typically north, east and down in a local geographic reference frame for instance).

Brief Summary Paragraph Right (3):
More recent developments have been directed towards the application of full inertial

navigation systems mounted in the probe, capable of providing "continuous" estimates of borehole position and angular orientation of the hole as the probe moves through it. Such systems also use gyroscopes and accelerometers, typically three of each, mounted with their sensitive axes mutually perpendicular to one another. The gyroscopes determine the angular motion of the probe from which its attitude relative to the reference frame may be derived, whilst the accelerometers measure the non-gravitational components of probe acceleration. The attitude information provided by the gyroscopes is used to resolve the accelerometer measurements into the designated reference frame. The resolved acceleration measurements are compensated in order to take into account the gravitational attraction of the Earth before being integrated twice with respect to time to generate estimates of probe velocity and position with respect to the reference frame.

Brief Summary Paragraph Right (4):
Inertial navigation system configurations may be classified under two major headings; platform or strapdown systems. In the former category, the inertial sensors (gyroscopes and accelerometers) are mounted on a stabilised platform so de-coupling the sensors from any rotational motion of the vehicle or probe in which they are installed and allowing gyroscopes with a relatively low dynamic range to be used. In strapdown configurations, the inertial sensors are attached rigidly (or via shock isolation mounts) to the vehicle causing the gyroscopes to be subjected to the maximum turn rates of the vehicle. Therefore, gyroscopes used in strapdown systems require a much larger dynamic range. In strapdown systems, the mechanical complexity of platform systems (the mechanical gimbal structure which supports the stable platform allowing its isolation from the angular motion of the vehicle and the associated components--slip rings, resolvers and torque motors) is discarded at the expense of a substantial increase in computational complexity.

Brief Summary Paragraph Right (5):
Whilst an on-board inertial navigation system (INS) is capable of providing estimates of probe position, velocity and attitude which are accurate in the short term, errors in these estimates drift or increase with time due mainly to imperfections in the inertial sensors and system errors. Whilst such effects may be minimised through the use of more accurate inertial sensors, assuming the required grade of sensor is available, and precise calibration of the sensors can be achieved, the cost penalties incurred soon become prohibitive, particularly to satisfy the accuracy requirements sought for borehole surveying applications. An alternative, and commonly used, method of overcoming such limitations is to operate an INS in conjunction with another navigation sensor or system, ideally one which has performance characteristics complementary to those of the INS, i.e. a sensor with good long term stability, but which is perhaps only capable of providing intermittent survey updates. For example, for systems operating on or above the surface of the Earth, improved navigation accuracy may be achieved through the use of a position fixing navigation aid, such as GPS satellite updates, thus enabling the drift errors in the IN system to be bounded.

Brief Summary Paragraph Right (6):
This approach usually provides a less costly alternative to the use of an unaided IN system with higher grade inertial sensors whilst the judicious combination of the two sources of information usually enables the resulting navigational data to be more accurate than that provided by either of the contributing systems when operated in isolation. The two sources of navigational information are combined using a filtering process, the filter being based upon a statistical error model of the INS and, in some applications, a model of the navigation aid as well. The manner in which the various sources of error propagate within an INS is well understood thereby allowing a representative dynamic model of the INS error propagation processes to be incorporated into the filter. A closed loop process is usually implemented which seeks to minimise the difference between the INS and aid measurements and predictions of this measurement difference derived from the error model(s). A particular, and often used, manifestation of this-filtering process, is known as Kalman filtering, in which the filter feedback gains are selected in an optimal manner with a view to minimising the covariances of the error differences.

Brief Summary Paragraph Right (7):
For systems operating underground, such as borehole navigation systems, the options for INS aiding are somewhat limited. One possible method for aiding a probe mounted

INS involves stopping the probe periodically during its descent/ascent in the borehole. Whilst the probe is stationary, any components of velocity indicated by the on-board INS are clearly error signals which can be used to update the INS velocity estimates and to form estimates of various errors in the system and in the measurements provided by the inertial sensors. Further schemes have been disclosed in which inertial navigation systems are aided using measurements of depth (cable length) using a Kalman filter.

Brief Summary Paragraph Right (9):
According to a first aspect of the invention there is provided a method of determining the path length along a borehole from a known reference point to a probe or tool which progresses through a drillpipe or tubular string, to provide data to aid an inertial-navigation system, comprising the steps of:

Brief Summary Paragraph Right (10):
According to a second aspect of the invention there is provided a method of determining the velocity of a probe or a tool moving through a drillpipe or tubular string to provide data to aid an inertial navigation system, comprising the steps of:

Brief Summary Paragraph Right (12):
According to a third aspect of the invention there is provided a method of determining the velocity of a probe or tool moving through a drillpipe or tubular string, to provide data to aid an inertial navigation system, comprising the step of using a flow measuring device to measure the velocity of by the probe or tool through the drillpipe or tubular string.

Brief Summary Paragraph Right (14):
The data representative of path length or velocity can be combined with data provided by an inertial navigation system using a filter, typically a Kalman filter, to reduce the errors in the data provided by the inertial navigation system.

Brief Summary Paragraph Right (15):
According to a fourth aspect of the present invention there is provided borehole survey apparatus comprising an inertial navigation system, within a probe or tool, for providing data representative of probe position, velocity and attitude, a sensing device for detecting joints between sections of drillpipe or tubular string within the borehole, means for determining the path length along the borehole from a known reference point to the probe or tool from the number of joints detected by the sensing device and a known length of each section of drillpipe or tubular string, and a filter for combining the data provided by the inertial navigation system and the aforesaid path length to reduce the errors in the data provided by the inertial navigation system.

Brief Summary Paragraph Right (16):
According to a fifth aspect of the present invention there is provided borehole survey apparatus comprising an inertial navigation system, within a probe or tool, for providing data representative of probe position, velocity and attitude, at least two sensing devices which are spaced apart by a known distance on the probe or tool, to detect one or more positions within the borehole, means for determining the velocity of the probe or tool string from the time elapsed between the two sensors detecting the location of each position and the distance between the sensors, and a filter for combining the data provided by the inertial navigation system and the aforesaid velocity to reduce the errors in the data provided by the inertial navigation system.

Brief Summary Paragraph Right (17):
According to a sixth aspect of the invention there is provided borehole survey apparatus comprising an inertial navigation system, within a probe or tool, for providing data representative of probe position, velocity and attitude, a flow measuring device for measuring the velocity the probe or tool through the drillpipe or tubular string within the borehole, and a filter for combining the date provided by the inertial navigation system and the aforesaid velocity to reduce the errors in the data provided by the inertial navigation system.

Drawing Description Paragraph Right (9):
FIG. 8 is a block diagram of a typical inertial navigation system showing the major

components and computational blocks of such a system and the application of correction terms at various modes or states in the inertial computational chain to correct or re-set those computational states.

Detailed Description Paragraph Right (5):
Referring now to FIG. 6 of the drawings, the output signal of the sensor 15 is fed into a processing circuit 17 which produces a signal representative of path length from the number of joints detected and the known length of each section of drillpipe or tubular string. The signal representative of path length is then combined with data provided by an inertial navigation system 18 mounted in the probe using a Kalman filter 19 to bound or reduce the errors in data provided by the inertial navigation system. In essence the Kalman filter 19, is a statistical weighting and error propagation device.

Detailed Description Paragraph Right (8):
FIG. 8 shows the main functional blocks of a strapdown inertial navigation system of the type which may be used in the context of this invention. This system comprises a sensor block 25, containing a triad of linear accelerometers 26 and rate gyroscopes 27, together with a signal processor 28 in which the navigation computation is implemented. This computation involves the processing of the gyroscope signals 29 which represent the angular rates of the probe to determine the attitude and heading of the accelerometer triad in the chosen navigation reference coordinate frame, which will typically be coincident with the directions of true north, east and the local vertical. This information is used to resolve the accelerometer measurements into the reference frame 30. The resolved accelerations form inputs to the navigation computation 31 in which these signal are combined with knowledge of the local gravity vector 32 and Coriolis corrections 33 to compute velocity and position of the probe with respect to an Earth fixed reference frame.

Detailed Description Paragraph Right (9):
FIG. 8 also shows the inertial navigation system update signals generated by the Kalman filter 34 which are to be used to correct the IN estimates of position, velocity and attitude as well as the measurements provided by the gyroscopes and the accelerometers.

Detailed Description Paragraph Right (13):
As shown in FIG. 7 the probe velocity determined by the two sensors 24 is combined with an estimate of velocity generated by the inertial navigation system using a Kalman filter 19.

Detailed Description Paragraph Right (16):
In general, the above embodiments relate to the use of strapdown or platform inertial navigational systems for borehole surveying and are applicable to systems incorporating conventional spinning mass gyroscopes, optical or vibratory gyroscopes and solid state, micro-machined, sensors.

CLAIMS:

1. A method of surveying a borehole containing sections of a tubular string utilizing a survey probe, the method comprising:

mounting an inertial navigational system on the probe, the inertial navigation system including a plurality of gyroscopes and a plurality of accelerometers;

generating a set of navigational data from the plurality of gyroscopes and the plurality of accelerometers indicative of the three dimensional probe position, velocity and attitude relative to the earth as the probe moves through the borehole;

having a probe mounted sensor for detecting joints a number of successive between the sections of the tubular string within the borehole;

using paid sensor for determining a path length along the borehole from a known reference point to the probe as a function of the number of joints detected; and

as the probe moves through the borehole, altering the navigational data as a function

of the determined path length to reduce errors in the navigational data provided by the inertial navigational system.

5. The method as defined in claim 1, further comprising:

mounting two sensors on the probe spaced apart axially a known distance, each of the two sensors detecting a fluid pressure in the tubular string;

determining a probe velocity while the probe moves through the tubular string as a function of the elapsed time between each of the two sensors detecting the same fluid pressure in the tubular string; and

as a probe moves through the borehole, altering the navigational data as a function of the determined probe velocity to reduce errors in the navigational data provided by the inertial navigation system.

7. A borehole survey apparatus for providing navigational data representative of the position of a probe moving within the borehole containing sections of a tubular string, the borehole survey apparatus comprising:

an inertial navigation system mounted on the probe, the inertial navigation system including a plurality of gyroscopes and a plurality of accelerometers for outputting a set of navigational data indicative of the three dimensional probe position, velocity and attitude relative to the earth as the probe moves through the borehole;

a sensor mounted on the probe for detecting a number of successive joints between the sections of the tubular string within the borehole; and

a signal processor mounted on the probe for receiving signals from said sensor and outputting a path length signal from a known reference point to the probe as a function of the number of joints detected by the sensor and altering the navigational data as the probe moves through the borehole as a function of the path length signal to reduce errors in the navigational data provided by the inertial navigation system.

10. The borehole survey apparatus as defined in claim 7, further comprising:

two sensors mounted on the probe and spaced axially apart a known distance, each of the two sensors detecting joints between the sections of the tubular string; and

the signal processor determining probe velocity while the probe moves through the tubular string as a function of the elapsed time between each of the two sensors detecting the same joint between the sections of the tubular string, and altering the navigational data as a function of the determined probe velocity to reduce errors in the navigational data provided by the inertial navigation system.

11. The borehole survey apparatus as defined in claim 7, further comprising:

two sensors mounted on the probe and spaced axially apart a known distance for detecting a fluid pressure in the tubular string; and

the signal processor determining a probe velocity while the probe moves through the tubular string as a function of the elapsed time between each of the two sensors detecting the same fluid pressure in the tubular string, and altering the navigational data as a function of the determined probe velocity to reduce errors in the navigational data provided by the inertial navigation system.

12. The borehole survey apparatus as defined in claim 7, further comprising:

a flow measuring device mounted on the probe; and

the signal processor determining probe velocity while the probe moves through the tubular string as a function of a flow measuring signal from the flow measuring device, and altering the navigational data as a function of the determined probe velocity to reduce errors in the navigational data provided by the inertial navigation system.

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L9: Entry 1 of 47 File: USPT Apr 3, 2001

DOCUMENT-IDENTIFIER: US 6211821 B1
TITLE: Apparatus and method for determining pitch and azimuth from satellite signals

Brief Summary Paragraph Right (2):
The present invention is related to navigational systems for vessels and flight vehicles and, more particularly, to a navigational apparatus for using satellite positional signals to determine pitch, azimuth, and position.

Brief Summary Paragraph Right (4):
It is known in the art to utilize a redundant set of north-seeking gyroscopes to determine the pitch and the heading, or azimuth, of a ship or aircraft. The function of the gyroscopes is to provide to a vessel, for example, an uninterrupted and continuously-smooth attitude reading to be used as an input to a rudder control loop and to the orientation function of a radar image.

Brief Summary Paragraph Right (5):
A set of two heading sensors is usually specified for most marine navigation. For vessels larger than 500 tons, there is a requirement that at least one of the heading sensors be certified by the International Marine Organization (IMO). This certification ensures that the navigation equipment meets reliability requirements. For these large vessels, the heading sensors must provide continuous heading, that is, there must be no significant heading outage under any circumstances. In addition, if the heading is linked to the auto-pilot or radar, the heading system must ensure that there are no rapid heading changes and the system must not output a heading that indicates a heading change opposite to the actual change in direction of the vessel.

Brief Summary Paragraph Right (6):
Gyrocompasses are typically used as the heading sensors. The cost of satisfying IMO requirements with a pair of gyrocompasses is about $200,000. While the use of gyrocompasses has proven to be reliable and has become the standard for shipboard navigation, the use of satellite positional signals in conjunction with a magnetic sensor can provide a low-cost and reliable alternative to at least one of the gyrocompass pair.

Brief Summary Paragraph Right (7):
While the art describes GPS systems used for determining position, azimuth, and pitch of a vessel or flight vehicle, there remains a need for improvements that offer advantages and capabilities not found in presently available devices, and it is a primary object of this invention to provide such improvements.

Drawing Description Paragraph Right (2):
FIG. 1 is a diagrammatical view of a navigation system in accordance with the present invention, including a magnetic sensor, heading sensor, and computational unit;

Detailed Description Paragraph Right (1):
FIG. 1 is a diagrammatical view of a navigation system 10 in accordance with the present invention. The navigation system 10 includes an integration unit 20 which receives data inputs from a magnetic sensor 30 and a heading sensor 40. The magnetic sensor 30 may be a magnetic compass. The beading sensor 40 is preferably a single-axis attitude sensor and is used to acquire a positioning signal 13 from a satellite 11, such as a Global Positioning System (GPS) satellite. The output signal 15 of the magnetic sensor 30 has slowly-changing biases but good continuity. The output signal

17 of the heading sensor 40 is unbiased but has intermittent integrity errors. The output signal 17 is used to correct the output signal 15. The corrected output signal 15 is used to ensure the integrity of the output signal 17 and to provide a continuous azimuth output 19 when the positioning signal 13 is poor or unavailable. By using the heading sensor 40 in accordance with the method described below, it is possible to produce azimuth and pitch readings with an accuracy of 0.4 degrees one sigma or better using a 1.0 meter baseline, and positional accuracy in the 5-20 cm range.

Detailed Description Paragraph Right (4):
User-supplied data 61 may also be provided to the computational unit 60. The user can define the azimuth and pitch offsets to be applied to the internally computed azimuth and pitch. This allows the user more flexibility when installing the navigation system 10, especially on aircraft and helicopters where the primary antenna 41 is located over the cockpit and the secondary antenna 43 is mounted close to the tail. In such a configuration, a 180.degree. heading offset is used to offset to provide the output of the heading sensor 40 with the same orientation as the actual vehicle heading. When installed in an aircraft, a pitch offset may also be input to provide a pitch reading of zero degrees for level flight.

Detailed Description Paragraph Right (13):
In way of example, there are approximately 64 million double-difference candidates, or 128 million single-difference candidates, in a search space encompassing twenty lanes for each of seven satellites. It can be shown that even low levels of multipath can result in having the correct set of ambiguity combinations appear to be less favorable than an erroneous set of candidates. To reduce the number of candidates, the search space is limited by imposing constraints on the baseline length, the pitch, the azimuth, or the velocity of the vessel or flight vehicle. Such constraints can be input by the user, in the same manner that offsets are input as described above, or the constraint data can reside in a memory device, such as a flash memory, or in RAM inside the computational unit 60. The reduction in the number of candidates when one or more constraints are imposed with a one meter baseline are summarized in Table 1.

CLAIMS:

8. A method for deriving an attitude, pitch or positional reading for a vessel or flight vehicle from signals transmitted by a plurality of positional satellites, said method comprising the steps of:

acquiring a set of primary positional signals from the plurality of satellites via a primary antenna;

acquiring a set of secondary positional signals from the plurality of satellites via a secondary antenna;

deriving post-correlation data from said sets of primary and secondary positional signals;

deriving a signal-to-noise ratio for each said positional signal from said post correlation data;

deriving a multipath estimate from said signal to noise ratios; and

estimating an azimuth or pitch reading from said multipath estimate.

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L24: Entry 6 of 25 File: USPT Jul 27, 1999

DOCUMENT-IDENTIFIER: US 5928309 A
TITLE: Navigation/guidance system for a land-based vehicle

Abstract Paragraph Left (1):
A navigation/guidance system uses a dead reckoning navigator with periodic GPS fixes to correct the drift of the inertial system. The navigation system primarily uses speed sensed by Doppler radar and attitude and heading sensed by a set of gyros. The navigation system uses various processes to compensate for any sensor errors. The system uses attitude data to compensate for GPS leverarm errors. The system can be used on a land-based vehicle to economically and accurately provide navigation data.

Brief Summary Paragraph Right (2):
The present invention relates to inertial navigation systems. More particularly, though not exclusively, the present invention relates to an inertial navigation/guidance system using a radio navigation receiver to correct the navigation errors.

Brief Summary Paragraph Right (5):
During airborne applications, the pilot generally has a large part of the area involved to be sprayed in view and the GPS antenna (mounted on top of the canopy) follows a relatively straight line when in an application swath. This provides for the required cross track position stability to obtain a well controlled application process.

Brief Summary Paragraph Right (6):
With ground rig applicators, such as tractors or floaters, the operator may have a limited view of the involved spray area and depending on the size/shape of the field and of the local ground cover it can be very difficult to determine where the previous swath coverage ends in order to proceed with the ensuing swath. A GPS antenna mounted on top of the ground vehicle (where it would be exposed to the GPS satellites) will experience large attitude excursions as the rig swaths the field. This results in GPS derived cross track position excursions relative to the vehicle ground track which would contaminate any attempt to parallel a defined field line. It can therefore be seen that there is a need for a better navigation/guidance system for use with a ground-based vehicle.

Brief Summary Paragraph Right (8):
Various prior art navigation systems for ground-based vehicles have several disadvantages. Systems using Doppler radar will encounter errors with the radar. Similarly, gyros will encounter drift errors which will continue to increase unless the drift error is corrected. Gyros that are inexpensive enough to be feasible to use may have drift rates high enough to make them unusable. For example, a typical inexpensive gyro sensor may have a drift rate uncertainty as high as 3600.degree. per hour which makes the gyro unusable for most applications. As a result, gyros have good short term characteristics but bad long term characteristics as the drift error becomes larger as time goes on.

Brief Summary Paragraph Right (10):
Various prior art systems navigating by GPS also have disadvantages. Prior art systems using GPS use GPS as the primary navigator. This intensifies the problems found with GPS. A GPS position calculation has a lag time. As a result, the position solution provided by a GPS receiver tells a user where the vehicle was a moment ago not in real

time. Another problem with GPS systems are the errors resulting from the antenna lever arm problem. A GPS antenna typically is a certain distance away from the GPS receiver. Since the GPS antenna is the collection point of the GPS signals received, the position solution will not accurately describe the position of the GPS receiver or some other reference point. If the geometrical distance between the GPS receiver or reference point and the GPS antenna is known, the position of the reference point may be calculated. However, as a ground based vehicle travels over uneven terrain such as terraces, slopes, ruts, bumps, etc., the actual position of the GPS antenna cannot be determined resulting in erratic GPS position solutions.

Brief Summary Paragraph Right (11):
Most prior art attempts to use a GPS navigation system attempted to deal with problems by correcting GPS drift and lag time. However no prior art system navigating by GPS has achieved the high accuracy and real time solutions required for applications requiring a high level of accuracy. The prior art attempts have not provided an adequate solution because GPS does not provide a continuous navigation solution. A GPS system will update its position periodically, not in real time, and a lag time is still involved. Another problem with a GPS system is the possibility of a signal dropout of the satellite signals. The accuracy of a GPS system is also limited due to the errors caused by the ionosphere. Another problem with GPS systems is that altitude data provided by a GPS receiver is not precise.

Brief Summary Paragraph Right (12):
Another problem with GPS systems is that a GPS system cannot accurately supply guidance data for a curved path. This problem relates to the lag time involved with GPS. A GPS system can only do linear interpolation of GPS position solutions which is inadequate for navigating a curved path. A GPS system also will not provide high quality heading information. Finally, the altitude calculated by a GPS receiver is inaccurate and unusable for certain applications.

Brief Summary Paragraph Right (14):
A further feature of the present invention is the provision of an inertial navigation/guidance system for use on a land-based vehicle.

Brief Summary Paragraph Right (15):
A further feature of the present invention is the provision of an inertial navigation/guidance system that senses the attitude of the vehicle.

Brief Summary Paragraph Right (16):
A further feature of the present invention is the provision of an inertial navigation/guidance system which uses a radio navigation receiver to correct the drift errors of the inertial system.

Brief Summary Paragraph Right (19):
A further feature of the present invention is the provision of an inertial navigation/guidance system which uses gyro information to compute the attitude and heading of the vehicle and a position change sensor to sense the speed of the vehicle.

Brief Summary Paragraph Right (20):
A further feature of the present invention is the provision of an inertial navigation/guidance system which uses accelerometers to measure the pitch and roll of the vehicle to refine the sensed attitude of the vehicle.

Brief Summary Paragraph Right (22):
A further feature of the present invention is the provision of an inertial navigation/guidance system which uses the sensed attitude of the vehicle to determine the position of the radio navigation antenna in order to correct the lever-arm error.

Brief Summary Paragraph Right (26):
The navigation and guidance system of the present invention provides accurate navigation data in real time using a dead reckoning navigator with periodic radio navigation fixes to correct for the drift of the inertial system. The system senses the speed, heading and attitude of the vehicle to determine a position of the vehicle. An external position reference provided by the radio navigation system is used to

correct any error in the determined position.

Brief Summary Paragraph Right (27):
The system is capable of correcting for the radio navigation antenna lever arm errors by using the attitude of the vehicle. The system may optionally be used on a ground or water based vehicle to provide navigation data and guidance commands to an automatic steering system. The system of the present invention may also be used on a agricultural vehicle to guide the vehicle through a field in a number of ways.

Drawing Description Paragraph Right (4):
FIG. 4 shows a functional block diagram of the dead reckoning navigation function of the present invention.

Detailed Description Paragraph Right (1):
The present invention will be described as it applies to its preferred embodiment. It is not intended that the present invention be limited to the described embodiment. It is intended that the invention cover all alternatives, modifications, and equivalences which may be included within the spirit and scope of the invention. While the present invention is described as being used on a land based vehicle, it is intended that the invention cover other applications. Also, the term land-based vehicle is meant to include vehicles on the ground or in the water, "land-based" is meant only to distinguish from airborne applications.

Detailed Description Paragraph Right (2):
The navigation/guidance system of the present invention is a dead reckoning navigator which uses periodic GPS fixes to correct the drift of the inertial system. The system uses GPS antenna attitude compensation to improve the accuracy of the GPS fixes. The system primarily uses speed sensed by Doppler radar and attitude and heading sensed by a set of gyros. As discussed above, systems using a Doppler sensor and gyros have the problem of errors in the sensors. In addition, in order to use inexpensive sensors, very large errors are encountered. The system uses various processes to compensate for the errors. The heading sensed by the gyros is aided by a magnetic heading compass and a GPS receiver. The speed sensed by the Doppler radar is also aided by the GPS receiver. The system also uses accelerometers to improve the accuracy of the system. A set of horizontal accelerometers measure the roll and pitch of the vehicle. This is used to provide the attitude integration algorithm (discussed below) with the vehicle horizontal rotations to more accurately calculate the attitude and heading.

Detailed Description Paragraph Right (3):
FIG. 1 shows the primary hardware elements of the inertial navigation/guidance system 10 of the present invention. The system 10 is comprised of a personal computer (PC) 12 which includes a CPU, memory and input/output electronics. Although the embodiment shown in the drawings shows a personal computer, the invention could use a processor circuit that includes a CPU, memory, and input/output electronics on a single processor card. A GPS receiver 14 plugs directly into an open PC expansion slot. Any GPS receiver suitable for use with the present invention may be used, however the preferred GPS receiver is the NovAtel GPS receiver card #951R. Alternatively, the system 10 could simply have a connector that would receive GPS data from any existing GPS receiver. Any other type of radio navigation system or combination of systems could be substituted for the GPS system such as LORAN, GLONASS, etc. A keyboard or keypad 16 is connected to the PC 12 and is used as a user interface to input data or control the system 10. A display unit 18 is also connected to the PC 12. The display unit 18 is used to display various information to a user. The display unit 18 could take on many forms, but is preferably comprised of a CRT display. The display unit could even be comprised of a display screen that shows the operator a graphic of a field or portion of the field and could indicate where the vehicle has been and where it is going. All sensor input data to the PC 12 will be digital serial. If any of the selected sensors provide only analog outputs, A/D converters will be used where required to obtain the appropriate input data formats. Also shown in FIG. 1 is a block diagram of the power supply circuit used by the present invention. The power supply circuit includes a 12 volt battery 32, a voltage converter 34 and a power supply 36. The power supply circuit provides the system 10 with 110 volts AC and a regulated DC voltage.

Detailed Description Paragraph Right (4):

A portable DGPS receiver 20 is also connected to the PC 12. The DGPS radio receiver 20 receives DGPS data for use by the PC to overcome the effects of Selective Availability (SA) as well as other imperfections in the time-coded signals broadcast by the NAVSTAR satellites. The use of DGPS provides a more accurate location solution than GPS alone. The DGPS radio receiver 20 may be any type of DGPS receiver suitable for use with the present invention but is preferably the Smartbase model number 10, manufactured by Premier GPS Inc. Also note that the present invention would work without using DGPS, although the accuracy may be less. One alternative to the preferred embodiment is to use a receiver that uses a combination of GPS and GLONASS signals to produce a more accurate radio navigation system.

Detailed Description Paragraph Right (5):
A GPS antenna 22 is connected to the GPS receiver 14 to provide the GPS receiver 14 with GPS signals from the NAVSTAR satellites. The GPS antenna 22 acts as the collection point for GPS signals received by the GPS receiver 14. The GPS antenna 22 is mounted to the host vehicle at a known location such that the location of the antenna 22 is always known relative to the GPS receiver 14 or some other reference point.

Detailed Description Paragraph Right (6):
As shown in FIG. 1, a number of sensors are also connected to the PC 12. Three rate gyros 24, three accelerometers 26, and a magnetic heading compass 28 are connected to the PC 12 to provide the system with various data. Preferably, the gyros 24, accelerometers 26 and the magnetic heading compass 28 are assembled together in a single unit. A position change sensor 30, preferably comprised of a Doppler radar is also connected to the PC 12 to provide the system with speed data. Although the preferred embodiment uses three each of the gyros 24 and accelerometers 26, more or less could be used. The choice of using two or three accelerometers depends on such factors as the level of accuracy desired, the application of the system, and the sophistication of the Kalman filter, etc. The gyros 24 act as angular change sensors, so therefore, any device with the same function could be substituted for the gyros 24. The preferred gyros are the model ENV-05H-02 manufactured by Murata Erie Co., Ltd. Similarly, the accelerometers 26 could be substituted by an equivalent device such an inclinometer, tilt sensors, etc. The preferred accelerometer is the model 02753-01 manufactured by Lucas Control System Products. The magnetic heading compass could also be substituted by any other heading sensor, for example, a fluxgate compass. The preferred magnetic heading compass is the model C100 manufactured by KVH Industries, Inc. Also note that the magnetic heading compass 28 is optional. Depending on the sophistication of the Kalman filter and other factors, the magnetic heading compass 28 may not be needed by the system. The Doppler radar 30 functions as a position change sensor, so therefore any equivalent device could be substituted for the Doppler radar such as an odometer or any other device used to derive the vehicle speed. The preferred Doppler radar is the model Radar II manufactured by Dickey-John.

Detailed Description Paragraph Right (7):
FIG. 2 shows a functional block diagram of the attitude/heading portion of the invention. The navigation/guidance system 10 uses software which performs the functions described and outlined in the figures. As described below, the attitude integration algorithm 42 uses the angular rates from the gyros 24, horizontal accelerations from the horizontal accelerometers 26, and heading and attitude error estimates from the other sensors to calculate a value for the vehicle's attitude (pitch and roll) and heading. The attitude and heading are primarily sensed by the gyros 24. The various sensors are used together as shown in the figures to obtain a more accurate value for attitude (pitch and roll) and heading. The data from the gyros 24 is applied the gyro compensator function 40 which applies constant values such as a scale factor, misalignment and fixed bias to the data and also applies changing values such as an estimated dynamic bias to the data. The data is then provided to the attitude integration algorithm 42 to calculate the attitude and heading. The horizontal accelerometers 26 provide data to the accelerometer compensation function 46 which applies constant values such as scale factor, bias, and misalignments to the data. The compensated data from the accelerometers 26 is then provided to a direction cosine matrix (shown in FIG. 2 as the body to navigation frame transformation function 48) and a platform leveling/damping function 50. The yaw attitude is slaved to the magnetic heading reference supplied by the magnetic heading compass 28. This, along with data from the GPS position are used by a blending filter 44 to provide a heading

error estimate to the attitude integration algorithm 42. A pitch and roll error estimate is also provided to the attitude integration algorithm 42. The pitch and roll error estimate is derived from data from the Doppler radar 30, the horizontal accelerometers 26, and the gyros 24.

Detailed Description Paragraph Right (8):
The attitude, heading and corresponding time are saved in a data table for interpolation to the GPS data time. This interpolated data is required to provide position corrections to the GPS position fix (see discussion of FIG. 3 below) for use in the dead reckoning navigation function shown in FIG. 4 (discussed below).

Detailed Description Paragraph Right (9):
FIG. 3 is a block diagram of the position correction function. As described above, the GPS receiver 14 is connected to the GPS antenna 22 to receive GPS data signals from the NAVSTAR satellites. The GPS receiver 14 also receives DGPS data from the DGPS radio receiver 20 to improve the GPS accuracy. The position corrections lc, Lc are calculated based on the latest position lr, Lr provided by the GPS receiver 14, the saved/interpolated dead reckoned position ls, Ls, and the GPS antenna moment arm (lever arm) corrections (discussed below) la, La based on the saved/interpolated attitude data corresponding to the GPS data time.

Detailed Description Paragraph Right (10):
The system uses the attitude data from the navigation system 10 for GPS antenna lever arm corrections. An antenna mounted on top of a vehicle such as a tractor or floater would be about 13 feet from the ground and will experience large attitude excursions as the vehicle swaths a field. As shown in FIG. 3, the system takes this into account by using the attitude data to make GPS position corrections based on the current attitude of the vehicle and the known position of the GPS antenna relative to the vehicle. As a result, as the vehicle travels over terraces, ruts, bumps, etc., the relatively large swings of the GPS antenna will not effect the accuracy of the GPS position. Using similar techniques, the position calculated by the system can be transferred to any part of the vehicle, for example to the end of a sprayer boom.

Detailed Description Paragraph Right (11):
FIG. 4 shows a block diagram of the dead reckoning navigation function. The velocity sensed by the Doppler velocity sensor 30 is transformed from mount to body axes, then transformed from body to local level axes using the attitude (pitch and roll) and heading data from the attitude integration algorithm 42 shown in FIG. 2. After the body to local level transform, the velocity is then transformed from local level to north referenced navigation axes. Finally, the data is provided to the position integration function 52 which is reset according to the available position correction values lc, Lc coming from the position correction function shown in FIG. 3.

Detailed Description Paragraph Right (12):
FIG. 5 shows a block diagram of the guidance function of the present invention. As shown in FIG. 5, the position of the vehicle determined by the position integration (FIG. 4) is supplied to a guidance algorithm 54 along with the vehicle's heading and the desired path. The guidance algorithm 54 uses this data to determine the cross track error and the heading error. From the cross track and heading errors, the system creates guidance commands. The guidance commands are provided to an operator perceivable display 56 and/or an automatic steering mechanism 58 (see discussion below). The display 56 may take on any form. The display 56 could be display unit 18 (discussed above), a light bar (discussed below), or any other type of operator perceivable indicator. The automatic steering mechanism 58 could also take on any form. For example, the steering mechanism could be a hydraulic steering mechanism.

Detailed Description Paragraph Right (13):
The navigation/guidance system of the present invention operates as follows. Before the host vehicle moves, the navigation system will initialize itself. The attitude (pitch and roll) is initialized by the accelerometers 26. The heading is initialized by the magnetic heading compass 28. The heading initialization is the most important initialization step. If the vehicle is moving the magnetic heading compass 28 will not be used to initialize the heading. The system is initialized based on where the operator of the vehicle indicates the vehicle is located and/or by GPS data. In other words, the operator can manually enter in the initial location and/or the system can

use the GPS location.

Detailed Description Paragraph Right (14):
Once the host vehicle begins moving the system 10 uses the various sensors to sense the movement of the vehicle. The attitude (pitch and roll) and heading of the host vehicle is sensed by the gyros 24. The speed of the vehicle is sensed by the Doppler radar 30. After sensing the attitude, heading, and speed, the system 10 calculates the velocity of the vehicle. The velocity of the vehicle is then integrated to determine the position of the vehicle. The system then uses a process to correct for errors in the system (see FIG. 3). The speed, heading and dead reckoning position errors are corrected by periodic GPS fixes. The attitude pitch and roll errors are corrected by sensing the acceleration caused by the motion of the vehicle. This is done via the accelerometers 26 and the knowledge of the vehicle speed and rotation rate. The accelerometers 26 sense the specific force accelerations acting on the vehicle including gravity, the acceleration of the vehicle, and centrifugal force. The gravity force is a known value and can be subtracted out. The remaining accelerations are then integrated to get a velocity. Similarly, the velocity and rotation rate of the vehicle are known and can be subtracted out. The remaining values can be used to correct the attitude errors.

Detailed Description Paragraph Right (15):
A vehicle using the navigation system 10 to help control a guidance system operates as follows and as described with FIG. 5 above. The primary information used by the guidance system from the navigation system 10 is the position of the host vehicle. As shown in FIG. 5, the guidance system receives a position signal from the navigation system 10 at a rate of 10 Hz. The guidance system also receives a vehicle heading signal from the navigation system 10 at a 10 Hz rate. Of course, the position and heading data could be received at any other suitable rate, but 10 Hz is the preferred rate. The desired path of the vehicle is provided to the guidance system from the processor memory, user input, or any other source. The guidance system computes cross track and heading error. Cross track error is the distance the vehicle is off from the desired path. Heading error is defined as the angular difference between the vehicle velocity and the desired path. The goal of the guidance system is to drive the cross track error to zero by guiding the vehicle along a desired path. The guidance algorithm 54 described above calculates the cross track error and the heading error to create guidance commands. These guidance commands are the steering signal used by the operator or by an automatic steering mechanism to steer the vehicle along the desired path.

Detailed Description Paragraph Right (16):
A vehicle equipped with the navigation system 10 of the present invention is capable of very accurately keeping track of where the vehicle is and where it has already been. This information can be used for any number of purposes or applications. The navigation system provides accurate, real time data sufficient to allow a guidance system to navigate along a curved path.

Detailed Description Paragraph Right (17):
With the navigation system 10 of the present invention used on an agricultural vehicle such as a tractor or floater, the vehicle would have many capabilities. An operator of the vehicle could manually steer through a path in the field and then use the system to guide the vehicle almost exactly parallel to the path on the next swath (see FIG. 7, discussed below). This would maximize the efficiency of the vehicle and make the operator's tasks easier and more reliable. Similarly, an operator of the vehicle could manually navigate the vehicle around the edge of a field and command the vehicle to automatically cover the remainder of the field within the outside path. Since the system would have the previous paths in memory, the system would know what portions of the field remain and would be able to cover the remainder of the field. The operator could also manually navigate around waterways and allow the system to automatically navigate around the waterways when they are encountered. The system could also be used to help control the operation of machinery such as sprayers, disks, etc. connected to the vehicles. For example, when a vehicle is turning around at the end of a field and is traveling over areas already sprayed, the sprayers could be automatically turned off until they reach a portion of the field not previously sprayed. Whatever the system is used for, the navigation information obtained could be saved and stored for subsequent operations in the same field. For example, once the system knows the

locations of borders, obstacles, etc. in a field, that information can be used later to automatically navigate around a field without "relearning" that information. That would make the system even more efficient after the initial operation in a particular field.

Detailed Description Paragraph Right (18):
FIG. 6 shows a tractor 60 incorporating the present invention. A GPS antenna 22 is mounted to the top of the tractor 60. The Doppler sensor 30 is mounted on the front of the tractor 60. The remaining components of the system 10 are also mounted to the tractor 60.

Detailed Description Paragraph Right (21):
Other applications of the present invention can be seen as well. For example, when the navigation/guidance system is applied to any other vehicle, many of the same advantages are found. In addition, given a typical $90,000 tractor, $60,000 of that cost goes toward the creature comforts such as a cab, air conditioning, etc. With a fully automatic guidance system, the operator and hence the creature comforts are not needed and $60,000 could be cut from the price of the tractor. The navigation/guidance system could also be used to quickly and efficiently survey land. With the system installed on a vehicle, for example a 4-wheeler, a user could simply drive over a given piece of land while the system keeps a record of precisely where the vehicle has been and the elevation at each point. This data could be transmitted or downloaded to a computer to be interpreted and used. Software such as CAD could then be used to create three dimensional maps of the surveyed land. Lawn services could use the navigation/guidance system with lawn sprayers or mowers as described above. Excavating machinery such as bulldozers could use the system to automatically excavate land. The navigation system is also capable of use on boats or ships. Vehicles traveling through water encounter similar problems as do vehicles traveling on the ground. For example, waves and strong winds as well as other forces can dramatically manipulate the attitude of ship causing problems described above such as the GPS antenna lever arm errors. The navigation system could also be used on boats to survey the bottom of bodies of water. An additional sensor such as sonar could be used to sense the depth of the water at every location that the boat traveled over. This data could be used to determine where silt build-up exists around dams for example. The rail industry could use the navigation/guidance system to keep track of and control trains. The navigation system will continue to operate even while the trains go trough tunnels or under foliage, etc. The railroads could fit more trains on a given track if they knew precisely where each train was. Also, the system is accurate enough to indicate which track a train is on, even where two tracks run parallel in close proximity. Regardless of how the present invention is used, the user will save time, labor, cost, etc.

Detailed Description Paragraph Right (22):
The preferred embodiment of the navigation system 10 of the present invention may be configured as follows. A sensor package is contained within a single enclosure. The sensor package includes the rate gyros 24, the accelerometers 26 and the magnetic heading compass 28. The sensor package could act as a stand-alone inertial measurement unit with the capability of connecting to a vehicle and any other sensors desired. The Doppler radar position sensor 30 is attached to the vehicle and preferably pointed downward toward the ground at an angle of about 30.degree.. A display head includes the display unit 18, the processor 12, the GPS receiver 14, a tactile device (e.g., a keypad or keyboard), the DGPS radio receiver and the required power supplies. Two antennas (one GPS and one DGPS) are attached to the vehicle and connected to the appropriate receiver. Finally, a light bar is installed on the vehicle in view of the operator and also connected to the display head. The light bar is comprised of a row of lights that indicate the magnitude and direction of the cross track error to the operator. In response to the light bar indication the operator could steer left or right in order to continue on a desired path. Optionally, the system 10 may provide guidance commands to an automatic steering mechanism.

Other Reference Publication (2):
P. Daum et al., Aided Intertial Land Navigation System (ILANA) with a Minimum Set of Inertial Sennsors, Position Location and Navigation Symposium (PLANS), Las Vegas, Apr. 11-15, 1994, 11 Apr. 1994, Institute of Electrical and Electronics Engineers, pp. 284-291, XP000489353 (see p. 284, right hand column).

CLAIMS:

1. A method of navigating a non-airborne vehicle comprising the steps of:

providing a position change sensor;

sensing the speed of the vehicle using the position change sensor;

providing an angular change sensor;

sensing the heading and attitude of the vehicle using the angular change sensor;

providing an accelerometer;

correcting the sensed attitude of the vehicle using data from the accelerometer, position change sensor and angular change sensor;

determining the position of the vehicle based on a known previous position and the sensed speed, heading, and attitude of the vehicle;

providing a radio navigation system;

storing positions of the vehicle each relative to a given point in time;

determining an external position reference for a given point in time using data from the radio navigation system; and

correcting any error in the determined position of the vehicle using the determined external position reference and comparing it to the stored position of the vehicle for the same point in time.

6. The method of claim 1 wherein said radio navigation system is comprised of a GPS system.

7. The method of claim 1 wherein said radio navigation system is comprised of a LORAN system.

8. The method of claim 1 wherein said radio navigation system is comprised of a GLONASS system.

9. The method of claim 1 further comprising the steps of:

providing a radio navigation antenna for use with the radio navigation system, said antenna having a known location relative to a reference point on the vehicle;

determining the position of the radio navigation antenna based on the attitude of the vehicle and the known location of the antenna relative to the reference point; and

determining the external position reference using data from the radio navigation system and using the determined position of the radio navigation antenna.

10. The method of claim 1 wherein the navigating comprises autonomous steering of the vehicle.

13. A navigation system for a non-airborne vehicle comprising:

a position change sensor for sensing the speed of the vehicle;

a set of gyros for sensing the attitude and heading of the vehicle;

a set of accelerometers for sensing the forces acting on the vehicle;

a radio navigation system for sensing an external position reference for a given point in time, said radio navigation system including an antenna coupled to said vehicle at a known location relative to the vehicle; and

a processor connected to each of said sensors and radio navigation system, said processor performing the processing steps of:

correcting the sensed attitude of the vehicle using the sensed forces acting on the vehicle;

determining the velocity of the vehicle using the sensed speed, heading and attitude of the vehicle,

determining a first position of the vehicle by integrating the determined velocity,

storing said first position of the vehicle each relative to a given point in time;

determining the position of the antenna based on the attitude of the vehicle and the known location of the antenna relative to the vehicle,

correcting the external position reference based on the determined position of the antenna, and

correcting the determined first position using the corrected external position reference by comparing it to the stored first position of the vehicle for the same point in time.

14. The navigation system of claim 13 wherein said position change sensor is comprised of a Doppler radar.

15. The navigation system of claim 13 wherein said set of gyros is comprised of two gyro sensors.

16. The navigation system of claim 13 wherein said set of gyros is comprised of three gyro sensors.

17. The navigation system of claim 13 wherein said radio navigation system is a GPS system.

18. The method of claim 17 wherein said radio navigation system further comprises a DGPS receiver.

19. The system of claim 13 wherein the navigating comprises autonomous steering of the vehicle.

21. The navigation system of claim 13 further comprising a guidance system port for providing data to a vehicle steering system.

22. The navigation system of claim 21 wherein said data provided to a vehicle guidance system relates to the vehicle position and heading.

23. The navigation system of claim 22 wherein said data also relates to a desired path.

24. The navigation system of claim 22 wherein said data comprises a steering command signal.

25. The navigation system of claim 21 wherein said data provided to a vehicle guidance system includes the cross track error and heading error.

26. A method of navigating a land-based agricultural vehicle through a field comprising the steps of:

sensing the speed of the vehicle;

providing an inertial sensor system;

sensing the heading and attitude of the vehicle using the inertial sensor system;

determining the position of the vehicle based on a known previous position and the sensed speed, heading, and attitude of the vehicle;

storing positions of the vehicle each relative to a given point in time;

providing a radio navigation system;

determining an external position reference for a given point in time using data from the radio navigation system;

producing true position data by correcting any error in the determined position of the vehicle using the external position reference and comparing it to the stored position of the vehicle for the same point in time; and

using the true position data to accurately navigate through a field.

27. The method of claim 26 further comprising the steps of:

providing a radio navigation system antenna coupled to the vehicle at a known location relative to the vehicle;

determining the position of the antenna based on the attitude of the vehicle and the location of the antenna relative to the vehicle; and

refining the determined external position reference based on the determined position of the antenna.

31. The method of claim 26 further comprising the steps of:

sensing the acceleration caused by the vehicle;

using the sensed acceleration caused by the vehicle to refine the determined position of the vehicle.

32. The method of claim 26 wherein said radio navigation system is comprised of a GPS.

33. The method of claim 26 further comprising the steps of determining the cross track error and heading error based on the true position data and a desired navigation path.

37. The method of claim 26 wherein said land based agricultural vehicle is comprised of a chemical sprayer.

38. The method of claim 26 wherein the navigating comprises autonomous steering of the vehicle.

41. A method of compensating for a radio navigation system antenna lever arm for a non-airborne vehicle comprising the steps of:

providing a radio navigation system antenna having a known location relative to a reference point on the vehicle;

providing an inertial system for sensing the angular changes of the vehicle;

determining the attitude of the vehicle using data from the inertial system; and

determining the position of the radio navigation system antenna based on the attitude of the vehicle and the known location of the radio navigation system antenna relative to the reference point.

42. A navigation system for a tractor comprising:

a position change sensor for sensing the speed of the tractor;

a set of gyros for sensing the attitude and heading of the tractor;

a set of angular change sensors for sensing the pitch and roll of the tractor;

a radio navigation system for sensing an external position reference for a given point in time, said radio navigation system including an antenna coupled to said tractor at a known location relative to the tractor;

a processor connected to each of said sensors and radio navigation system, said processor performing the processing steps of:

correcting the sensed attitude of the tractor using the sensed pitch and roll of the tractor;

determining the velocity of the tractor using the sensed speed, heading and attitude of the tractor,

determining a first position of the tractor by integrating the determined velocity,

storing said first positions of the vehicle each relative to a given point in time;

determining the position of the antenna based on the attitude of the tractor and the known location of the antenna relative to the tractor,

correcting the external position reference based on the determined position of the antenna, and

correcting the determined first position using the corrected external position reference by comparing it to the stored position of the vehicle for the same point in time;

an output port connected to said processor for providing data to a tractor guidance system.

43. The navigation system of claim 42 further comprising a user perceivable display connected to said processor for displaying information.

44. The navigation system of claim 43 wherein said display is comprised of a light bar mounted on the tractor.

45. The navigation system of claim 42 wherein said data is comprised of the cross track error and the heading error.

46. The navigation system of claim 42 wherein said tractor guidance system is comprised of an automatic steering system.

47. The navigation system of claim 46 wherein said data is comprised of guidance commands for the automatic steering system.

49. A method of navigating a moving non-airborne vehicle comprising the steps of:

(a) sensing the speed of a vehicle;

(b) sensing the heading and attitude of the vehicle from a known initialization position using an inertial sensor system having inherent drift that increases over time;

(c) estimating in real time the position of the vehicle for discrete points in time based on steps (a) and (b);

(d) storing the estimates correlated to the discrete points in time;

(e) correcting error between estimated position and actual position by periodically determining actual position correlated to discrete points in time of the vehicle,

comparing a stored estimated position with an actual position for the radio navigation system, and adjusting estimated position if the comparison falls outside a predetermined range;

thus periodically producing real-time true position data for navigation of the vehicle by correcting for the inherent drift of the inertial sensor system, by periodically, if needed, comparing past estimated and past actual position and adjusting, if, needed, therebetween.

50. The method of claim 49 wherein the navigating comprises autonomous steering of the vehicle.

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Terms	Documents
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Set Name side by side	**Query**	**Hit Count**	**Set Name** result set
	DB=USPT,PGPB,JPAB,EPAB,DWPI,TDBD; PLUR=YES; OP=ADJ		
L24	L23 and l22	25	L24
L23	vehicle near accelerat$3	15564	L23
L22	L21 and l1 and l3	92	L22
L21	integrat$3 near accelerat$4	1440	L21
L20	L19 and l15 and l1 and l3	1	L20
L19	L17 near (map or display)	182	L19
L18	L17 and l16	199	L18
L17	(position or location) near angular	100179	L17
L16	L15 and l1 and l3 and (position or location)	8172	L16
L15	map	143949	L15
L14	l13 and l1 and l3	40	L14
L13	L10 near align$3	10401	L13
L12	L11 and l3	3935	L12
L11	L10 and l1	26616	L11
L10	optic$3 or refelect$3	1378367	L10
L9	L8 and l3	47	L9
L8	L7 and l6	57	L8
L7	(look$3 or search$3 or seek$3) near north	468	L7
L6	L2 and l1	2436	L6
L5	L4 and l1	16	L5
L4	(position or location) near (rotat$4 or around) near axis	1618	L4
L3	vehicle	1245098	L3
L2	gyroscope	12427	L2
L1	gps or navigation	405575	L1

END OF SEARCH HISTORY

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L18: Entry 29 of 199 File: USPT Mar 26, 2002

DOCUMENT-IDENTIFIER: US 6362776 B1
TITLE: Precision radar altimeter with terrain feature coordinate location capability

Abstract Paragraph Left (1):
A radar altimeter for determining altitude of an air vehicle comprises a transmitter for transmitting radar signals toward the ground. A first and a second antenna receive reflected radar signals from the ground. A signal processor is coupled to the first and the second antennas. The signal processor includes filter means for rejecting signals other than signals reflected from a selected ground swath. The signal processor determines the above ground level altitude of the air vehicle based on the radar signals output from the filter means. A phase ambiguity resolution means resolves phase ambiguities that arise due to multiple wavelength separation of the first and the second antenna. The signal processor also determines the horizontal position of the highest point in the selected ground swath. In a preferred embodiment, the phase ambiguity resolution means comprises a third antenna spaced closely to the first antenna such that there are no phase ambiguities between the reflected radar signals received by the third antenna and the first antenna.

Brief Summary Paragraph Right (2):
The present invention relates to a radar altimeter, and more particularly to a precision radar altimeter with terrain feature coordinate location capability.

Brief Summary Paragraph Right (3):
The precision radar altimeter of the present invention "looks" at the ground in a series of swaths, using doppler band pass filters to focus in on one swath at a time. Return signals are received by a pair of antennas. The location of the highest point within a particular swath is determined by performing phase comparisons of the return signals received by the two antennas. If the highest point being illuminated by radar is directly below the air vehicle, then the return signal will come back at the same time to both antennas. On the other hand, if the highest point is off to one side of the air vehicle, the return signal will come back to one antenna before it comes back to the second antenna, because the path is longer for the second antenna. The phase or the time of arrival of the return signals at each of the antennas are compared. The greater the distance between the two antennas, the more accurate the measurement will be. However, as the distance between the two antennas increases, one or more phase ambiguities result.

Brief Summary Paragraph Right (4):
A phase ambiguity may be understood in the context of a phasor. A phasor repeats every 360 degrees. Therefore, 370 degrees will appear the same as 10 degrees, 380 degrees will appear the same as 20 degrees, and so on. The further apart the two antennas are spaced, the more phase ambiguities will result. Very complex, costly and power consuming ambiguity reducing algorithms are typically incorporated into systems to reduce or eliminate the phase ambiguities. Furthermore, existing systems are "side-looking", meaning that the antennas for the radar are pointed off to the side of the air vehicle. Side-looking systems process all range cells within a doppler swath, which requires a high level of processing, resulting in large and costly systems. These side-looking radars generate elevation features of the entire area off to the side of the vehicle. These features are correlated with existing electronic terrain elevation maps for navigation purposes. Additionally, the side-pointing antennas must be configured to not illuminate the terrain on the opposite side of the vehicle during roll maneuvers, resulting in rather complex antenna steering mechanisms. The size,

weight and cost of existing systems makes it difficult to incorporate the systems on small and medium sized air vehicles.

Brief Summary Paragraph Right (6):
A radar altimeter system and method for determining terrain feature location and altitude of an air vehicle comprises a transmitter for transmitting radar signals toward the ground. A first and a second antenna receive reflected radar signals from the ground. A signal processor is coupled to the first and the second antennas. The signal processor includes doppler filter means for rejecting signals other than signals reflected from a selected ground swath. The signal processor determines the above ground level altitude of the air vehicle based on the radar signals output from the filter means. A phase ambiguity resolution means resolves phase ambiguities that arise due to multiple wavelength separation of the first and the second antenna. The signal processor also determines the position of the highest point in the selected ground swath. In a preferred embodiment, the phase ambiguity resolution means comprises a third antenna spaced closely to the first antenna such that there are no phase ambiguities between the reflected radar signals received by the third antenna and the first antenna.

Detailed Description Paragraph Right (1):
FIG. 1 shows a block diagram of a precision radar altimeter according to the present invention. In a preferred embodiment, radar altimeter 8 is incorporated in an air vehicle. Radar altimeter 8 includes three channels--phase ambiguity channel 9A, phase A channel 9B and phase B channel 9C. Channel 9A includes antenna 10A, receiver 34A and digitizer 18A. Receiver 34A includes low noise amplifier (LNA) 12A, mixer 14A and intermediate frequency (IF) amplifier 16A. Channel 9B includes antenna 10B, receiver 34B and digitizer 18B. Receiver 34B includes LNA 12B, mixer 14B and IF amplifier 16B. Channel 9C includes antenna 10C, transmit/receive switch 11, receiver 34C and digitizer 18C. Receiver 34C includes LNA 12C, mixer 14C and IF amplifier 16C. Transmit/receive switch 11 in channel 9C allows channel 9C to operate in either a transmit mode or a receive mode.

Detailed Description Paragraph Right (3):
The radar altimeter of the present invention provides cross-track and vertical distance to the highest object below the air vehicle in, for example, ten foot wide down-track swaths, which are bounded by an antenna pattern that is approximately 46 degrees wide in the cross-track direction. "Down-track" means in the direction of travel. "Cross-track" means perpendicular to the direction of travel. Other antenna patterns and swath characteristics may be used. The downtrack width of a swath varies with the altitude of the air vehicle.

Detailed Description Paragraph Right (7):
Computer 33 receives air vehicle or aircraft (A/C) vertical and horizontal velocity data from the air vehicle's inertial navigation system (INS). Computer 33 processes the velocity data and outputs control signals to DSP 30 on control lines 45. DSP 30 outputs target position vectors identifying the position of the highest point within particular regions or "swaths" on the ground, and also outputs above ground level (AGL) altitude data that identifies the vehicle altitude.

Detailed Description Paragraph Right (8):
FIG. 2 shows a second block diagram of the radar altimeter of the present invention, including additional detail regarding DSP 30. RF oscillator 20, clock 26 and computer 33 are not shown in FIG. 2 in order to simplify the diagram and provide additional space for other components. DSP 30 includes range gate/correlators 36A-36D, word integration band pass filters (BPFs) 38A-38D, image reject mixers 40A-40D, doppler band pass filters (BPFs) 42A-42D, range processor 44, coarse phase processor 46A, coordinate location processor 46B and fine phase processor 46C. Coarse phase processor 46A, coordinate location processor 46B and fine phase processor 46C are collectively referred to as phase processor 46. DSP 30 includes 4 channels--range channel 9D, phase B channel 9C, phase ambiguity channel 9A and phase A channel 9B. Range channel 9D includes blocks 36D-42D and 44. Phase B channel 9C includes blocks 36C-42C. Phase ambiguity channel 9A includes blocks 36A-42A. Phase A channel 9B includes blocks 36B-42B.

Detailed Description Paragraph Right (11):

The horizontal location of the highest point within a particular swath is determined by performing phase comparisons of the return signals. If the highest point being illuminated by radar is directly below the air vehicle, then the return signal will come back at the same time to antennas 10B and 10C. On the other hand, if the highest point is off to one side of the air vehicle, the return signal will come back to one antenna (e.g., antenna 10B) before it comes back to the second antenna (e.g., antenna 10C), because the path is longer for the second antenna 10C. The phase or the time of arrival of the return signals at each of the antennas is compared. The greater the distance between the two antennas 10B and 10C, the more accurate the measurements will be. However, as the distance between antennas 10B and 10C increases, one or more phase ambiguities result. The further apart antennas 10B and 10C are spaced, the more phase ambiguities will result. At a typical antenna separation according to the present invention, four or five phase ambiguities occur.

Detailed Description Paragraph Right (14):
FIG. 3 illustrates the search-while-process technique performed by the radar altimeter of the present invention. As shown in FIG. 3, air vehicle 60 is flying over terrain 70. Range gate/correlators 36A-36C within DSP 30 are fixed on the nearest target in the present doppler swath 62. At the same time, range gate/correlator 36D is searching the slant range to the highest object in the next doppler swath 64. Slant range is essentially the same as time (i.e., the time for a return signal to be received). Control lines 45A and 45B (shown in FIG. 2 and collectively referred to as control lines 45) are used to define the swath characteristics. Computer 33 (shown in FIG. 1) outputs control signals to doppler BPFs 42A-42D on control lines 45 based on air vehicle altitude data from range processor 44 (shown in FIG. 2), and velocity data received from the air vehicle's INS. The doppler frequency and bandwidth for BPFs 42A-42D are adjusted based on the air vehicle velocity and altitude data to obtain appropriate swaths. Computer 33 uses control line 45A to limit doppler BPF 42D to next doppler swath 64, and uses control line 45B to limit doppler BPFs 42A-42C to present doppler swath 62.

Detailed Description Paragraph Right (16):
FIG. 4 is a timing diagram further illustrating the search-while-process function. In a preferred embodiment, air vehicle 60 is moving at a velocity of approximately 500 knots or about 800 feet per second, so it takes about 12 msec to go through each 10 foot swath. Each column of FIG. 4 represents a 12 msec interval. The 12 msec interval is referred to as a swath interrogation interval. The first row of FIG. 4 indicates the air vehicle or aircraft (A/C) position. The second row of FIG. 4 indicates the swath currently being processed by range channel 9D. The third row of FIG. 4 indicates the swath currently being processed by phase channels 9A-9C. Range channel 9D is always one swath ahead of phase channels 9A-9C. At the end of each 12 msec interval, range channel 9D provides channels 9A-9C with the detected range for the next swath to be processed by channels 9A-9C.

Detailed Description Paragraph Right (19):
During each 12 msec swath interrogation interval, samples from approximately 600 pulses are passed from digitizer 18A to range gate/correlator 36D. For the entire 12 msec, the position of range gate/correlator 36D is moved with respect to the previously determined slant range in an attempt to find the highest point (i.e., the first point with non-zero energy). At the end of the 12 msec interval, range processor 44 sets range gate/correlators 36A-36C to the slant range corresponding to the highest target. Range processor 44 continuously integrates or averages the highest terrain points, effectively filtering the data to provide altitude.

Detailed Description Paragraph Right (20):
Each channel 9A-9D in DSP 30 includes essentially the same components. In a preferred embodiment, all of the components of DSP 30 are implemented in software, although hardware could also be used. Range gate/correlators 36A-36D phase demodulate the samples received from digitizers 18A-18C. Also, to provide immunity against jammers and intercept receivers and mutual interference from other vehicles, range gate/correlators 36A-36D and word integration band pass filters 38A-38D reject all signals except the signals that were transmitted by transmitter 32. In a preferred embodiment, the signals transmitted by transmitter 32 are phase coded so that return signals with a code different than that transmitted are rejected by correlators 36A-36D and filters 38A-38D. Range gate/correlators 36A-36D demodulate the coded radar

return signals and output the sampled return signals to word integration band pass filters 38A-38D. Word integration band pass filters 38A-38D integrate the received samples and generate an intermediate frequency digitally sampled sine wave, which is output to image reject mixers 40A-40D. Word integration band pass filters 38A-38D also function as a correlator, rejecting codes that do not correlate. The demodulation/filter action results in the rejection of undesirable signals.

Detailed Description Paragraph Right (22):
Doppler BPFs 42A-42C are set to a center frequency corresponding to the doppler shift for the present swath 62. In like manner, doppler BPF 42D is set to a center frequency corresponding to the doppler shift for the next doppler swath 64. The bandwidth for doppler BPFs 42A-42D is set to provide a desired downtrack swath width, such as 10 feet. Each doppler BPF 42A-42C outputs a sine wave. Each sine wave output by doppler BPFs 42A-42C is at the same frequency, but the sine waves will have different phase shifts. Based on the phase differences of the sine waves received from doppler BPFs 42A-42C, phase processor 46 determines the angular position of the highest point in the present swath, including whether the highest point is to the right or the left of the air vehicle. Phase processor 46 also eliminates any phase ambiguity based on phase comparisons of the various input signals. In a preferred embodiment, coarse phase processor 46A determines the phase relation between the signals from doppler BPF 42C and doppler BPF 42A, and outputs an unambiguous but coarse phase relation. Fine phase processor 46C determines the phase relation between the signals from doppler BPF 42C and doppler BPF 42B, and outputs a fine but ambiguous phase relation. Coordinate location processor 46B determines height and horizontal location of the highest point in a swath based on the fine-ambiguous and coarse-unambiguous information from phase processors 46A and 46C, and outputs a target position vector.

Detailed Description Paragraph Right (24):
Unlike the search-while-process technique in which range channel 9D was one swath ahead of air vehicle 60, and phase channels 9A-9C were at the same swath as air vehicle 60, in the single swath technique, all of the channels 9A-9D are one swath behind the current air vehicle position. As air vehicle 60 flies over a first ground swath, digitizers 18A-18C digitize the return signals for the first ground swath and store the data in RAMs 19A-19C. Range channel 9D and phase channels 9A-9C process the first swath data stored in RAMs 19A-19C as air vehicle 60 is flying over a second swath (i.e., the present swath). Therefore, doppler BPFs 42A-42D are each set to the past doppler swath, or the swath just passed by air vehicle 60. As air vehicle 60 flies over a third swath, the radar return signals for the third swath are stored in RAMs 19A-19C while channels 9A-9D process return signals from the second swath, and so on. Other than the differences described above, radar altimeter 80 operates substantially the same as the embodiment shown in FIGS. 1 and 2 and described above.

Detailed Description Paragraph Right (25):
The radar altimeter of the present invention may be used in many different applications. For example, the radar altimeter can be used in an unmanned air vehicle. In such an application, an electronic terrain elevation map is stored in the unmanned air vehicle. The unmanned air vehicle compares the output of the radar altimeter of the present invention with the stored terrain elevation map, and determines where the air vehicle is located. The radar altimeter of the present invention may also be used as a back-up to a global positioning system (GPS) in the event that the GPS becomes ineffective due to jamming, signal blockage, or other problems.

CLAIMS:

1. A radar altimeter for determining altitude of an air vehicle with respect to ground, the radar altimeter comprising:

a transmitter for transmitting radar signals toward the ground;

a first and a second antenna for receiving reflected radar signals from the ground;

a signal processor coupled to the first and the second antennas, the signal processor including filter means for rejecting signals other than signals reflected from a selected ground swath, the signal processor determining the above ground level altitude of the air vehicle based on the radar signals output from the filter means;

and

phase ambiguity resolution means for resolving phase ambiguities that arise due to multiple wavelength separation of the first and the second antenna.

2. The radar altimeter of claim 1, wherein the signal processor determines the position of the highest point in the selected ground swath.

4. The radar altimeter of claim 1, wherein the signal processor includes a range channel for calculating the above ground level altitude of the air vehicle with respect to a first ground swath, and includes at least two phase channels for calculating the position of the highest point in a second ground swath, the range channel and the phase channels operating simultaneously.

6. The radar altimeter of claim 1, and further comprising a memory for storing received radar signals for a first ground swath, the signal processor processing the received radar signals for the first ground swath to determine the above ground level altitude of the air vehicle and the position of the highest point in the first ground swath as the air vehicle flies over a second ground swath.

8. A method of determining altitude of an air vehicle with respect to ground, the method comprising:

transmitting radar signals toward the ground;

receiving reflected radar signals from the ground with a first and a second antenna;

filtering the received radar signals to pass only those signals reflected from a selected ground swath;

determining the altitude of the air vehicle based on the radar signals reflected from the selected ground swath; and

comparing the reflected radar signals received by the first antenna with signals received by a third antenna to resolve phase ambiguities that arise due to multiple wavelength separation of the first and the second antenna.

9. The method of claim 8, and further comprising:

determining the position of the highest point in the selected ground swath.

10. The method of claim 8, and further comprising:

calculating the above ground level altitude of the air vehicle with respect to a first ground swath using a range channel;

calculating the position of the highest point in a second ground swath using at least two phase channels, the range channel and the phase channels operating simultaneously.

12. The method of claim 8, and further comprising:

digitizing received radar signals for a first ground swath;

storing the digitized radar signals for the first ground swath; and

processing the digitized radar signals for the first ground swath to determine the above ground level altitude of the air vehicle and the position of the highest point in the first ground swath as the air vehicle flies over a second ground swath.

14. A down-looking precision radar altimeter for determining altitude of an air vehicle with respect to ground, the radar altimeter comprising:

a transmitter for transmitting radar signals substantially straight down toward the ground under the air vehicle;

a first and a second antenna for receiving reflected radar signals from the ground, the received radar signals being reflected from terrain on both a left and a right side of the air vehicle;

a signal processor coupled to the first and the second antennas, the signal processor including filter means for rejecting signals other than signals reflected from a selected ground swath, the signal processor determining the above ground level altitude of the air vehicle based on the radar signals output from the filter means.

15. The radar altimeter of claim 14, wherein the signal processor determines the position of the highest point in the selected ground swath.

18. The radar altimeter of claim 14, wherein the signal processor includes a range channel for calculating the above ground level altitude of the air vehicle with respect to a first ground swath, and includes at least two phase channels for calculating the position of the highest point in a second ground swath, the range channel and the phase channels operating simultaneously.

20. The radar altimeter of claim 14, and further comprising a memory for storing received radar signals for a first ground swath, the signal processor processing the received radar signals for the first ground swath to determine the above ground level altitude of the air vehicle and the position of the highest point in the first ground swath as the air vehicle flies over a second ground swath.

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L20: Entry 1 of 1 File: USPT Oct 11, 1977

DOCUMENT-IDENTIFIER: US 4053893 A
TITLE: Method of and apparatus for indicating the geographical position of a pilot vehicle

Assignee Name (1):
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Abstract Paragraph Left (1):
The present invention relates to a method of and apparatus for indicating e geographical position of a piloted vehicle equipped with a computer, the method comprising the steps of using a geographical map or a portion of map, approximately orientated, without regard to its method of folding and its dimensions; identifying and transmitting to the computer at any desired moment, basic information such as reference of alignment on a meridian of the map-references of magnetic declination and scale of said map, co-ordinates of at least one radio-navigation transmitter chosen on the map, co-ordinates of at least one objective to be reached on the map, co-ordinates of at least one possible intermediate point on the route; indicating on said map at any instant under the control of the computer which also receives the variable radio-navigation information from the transmitter selected, the geographical position of the vehicle, the above identification and indication steps being effected by the use of a single organization of means.

Abstract Paragraph Left (2):
The apparatus includes a slot having access to three sides for receiving the map which is immobilized, folded and roughly orientated, behind a double-glazed window, the means for alignment ~~with a meridian of~~ the map being constituted by pointers brought into coincidence with the meridian and means for supplying the computer with information of the angular position of said map with respect to the indicator.

Abstract Paragraph Left (3):
The vehicle is especially but not exclusively a flying vehicle.

Brief Summary Paragraph Right (1):
The present invention is concerned with a method and an apparatus for indicating in a continuous manner to the pilot of a vehicle (especially but not exclusively a flying vehicle) his geographical position shown on a map.

Brief Summary Paragraph Right (3):
Map systems unrolled by electro-mechanical means;

Brief Summary Paragraph Right (4):
MAP SYSTEMS PROJECTED BY OPTICAL MEANS (FILMS);

Brief Summary Paragraph Right (5):
SYNTHETIC MAP SYSTEMS GENERATED ELECTRONICALLY.

Brief Summary Paragraph Right (6):
These systems have certain disadvantages which restrict their general use: they are

bulky, heavy, expensive and for those which give indications on the ground infrastructure and the routes to be followed, the time required for bringing the maps up-to-date is relatively long. Furthermore, in respect of the last category, the risks of error in the charging of the memories are also high.

Brief Summary Paragraph Right (7):
These equipments are essentially employed on combat vehicles and on few air-line machines.

Brief Summary Paragraph Right (8):
The present invention enables inter alia these disadvantages to be reduced due to the fact that it does not put into memory a specific map system, but on the contrary is organized so as to utilize suitable maps extracted from the documentation proper to the crew, published and brought up to date much more frequently, and in any case they do not increase the risk of error in the infrastructure information utilized by the crew.

Brief Summary Paragraph Right (9):
The invention relates to a method which is characterized in that it makes use of a geographical map or a portion of map, approximately orientated, irrespective of its folding system and its size, and in that it consists, by means of a single organization of means, on the one hand of identifying and transmitting to a computer, at any selective moment, basic information, and on the other hand of indicating at any instant on the map, under the control of the said computer which also receives variable radio-navigation information, the geographical position of the vehicle.

Brief Summary Paragraph Right (10):
The method consists also of concentrating the function of identification of basic coordinates and the function of indication of geographical position on a single figurative point capable of being displaced above the map, on the one hand by the user himself and on the other hand automatically under the control of the computer.

Detailed Description Paragraph Right (2):
In the upper portion is formed a window 5 through which is observed the reference map C which has been inserted in the slot 1 of the apparatus.

Detailed Description Paragraph Right (10):
A control level 6 (FIG. 2) actuates a system of two arms 7 fixed to each other by a transverse shaft 8. On the two arms rests a plate 9 intended to force the map against the internal face of the window 5. A spring 10 compressed by one of the arms facilitates locking in the top position and prevents accidental release. In the position "unlocking", the level 6 transmits by means of a micro-contact (not shown) continuous information for the resetting to zero of the memories of the computer.

Detailed Description Paragraph Right (11):
The map folded in such manner as to show the useful zone in the perimeter of the window is inserted between the pressure plate and the internal face of the window, in a position such that the meridional lines are approximately vertical, the North of the map being at the top of the window. Operation of the locking lever 6 results in the immobilization of the map by forcing it against the internal face of the window.

Detailed Description Paragraph Right (12):
In the case where the appropriate map has remained in the apparatus from the previous flight with the pressure system locked, it is not necessary to remove it.

Detailed Description Paragraph Right (13):
When the system is under voltage with the map inserted and locked, the computer lights up a signal "Alarm A" (FIG. 1) indicating to the user that he must carry out the sequence giving the basic indications necessary for the calculation.

Detailed Description Paragraph Right (14):
Two fork-shaped independent pointers 11 are located between the glasses of the window, which is double-glazed or transparent plate and these pointers are controlled from the exterior by knobs 12 placed on the edge of the window, at the top and at the bottom of this latter and are brought by the user into coincidence with the same meridional line

shown on the map. The fork-shape permits the pointers to be placed to the best advantage, irrespective of the conditions of flight, the fork of each pointer being placed astride the line.

Detailed Description Paragraph Right (15):
Two associated potentiometers 13 then supply the computer with the angular position information of the map with respect to the indicator, this information being a function of the respective positions of the pointers.

Detailed Description Paragraph Right (17):
The indicator A being again lighted, the user registers the magnetic declination indicated on the map by means of a knob D moving a pointer in front of a graduated scale.

Detailed Description Paragraph Right (19):
In the same manner and for the same reasons, the indicator A goes out for one second. When the indicator is again lighted, the user registers numerically the scale of the map in the event of this differing from that of the map utilized for the previous flight, by acting on three pancake rollers E (FIG. 1), numbered from 0 to 9, the extreme right-hand roller indicating the tenths of nautical/inch. A coding system associated with the rollers transmits the scale value adopted which is memorized by pressing the push-button I. The indicator A is extinguished and only re-lights in the case of a fault or a test in course of operation. On the left-hand side of the front face (FIG. 1) are provided three push-buttons with mechanical locking (DME, VOR1-VOR2) on which it has been seen above that they must be in the "Out" position at the beginning of the utilization procedure. Each of them is accompanied by a small indicator 14.

Detailed Description Paragraph Right (20):
These push-bottons permit the selection of the type of radio-navigation reference as a function of the beacons utilized during the course of the flight considered.

Detailed Description Paragraph Right (22):
The user proceeds first of all to the selection of the frequency on the receivers. Then he depresses the push-button DME. The corresponding indicator lights-up, showing him that the servocontrols which actuate the displacement of a wire 15 (FIG. 2) carrying a figurative point 16 are at his disposal. The user then acts on a knurled knob G (longitude) in such manner as to cause the wire to pass through the point on the map representing the beacon DME. The knurled knob provided with a return to zero and associated with a potentiometer, acts through the intermediary of the output stage of the computer on a motor 17.

Detailed Description Paragraph Right (25):
When the wire has been placed in the desired position, the user acts on a knurled knob L (latitude) in such manner as to place the figurative point on the point of the map which represents the beacon.

Detailed Description Paragraph Right (28):
The figurative point being then in correspondence with the point of the map which represents the beacon, the user memorizes the position information by means of the push-button I. This information is given to the computer by the wound potentiometers. The taking into account of the information by the memory has the effect of extinguishing the indicator associated with the push-button DME. The knurled knobs are inoperative and the computer holds the mechanism stopped, waiting for a second reference.

Detailed Description Paragraph Right (33):
This information is treated as shown diagrammatically in FIG. 3 while taking account of the corrector terms put into memory of computer O in such manner as to generate two signals U(x) and V(y) from computer O controlling respectively the motors 17 and 26. The point 16 representing the moving body takes up a position at a point which indicates the actual position of the aircraft with respect to the map C. During the course of the flight, the computer constantly treats the information from the receivers R of VOR and DME signals, and the point 16 describes on the map the continuous trajectory of the aircraft, instantaneously informing the user of its

position and thereby reducing the differences and corrections.

CLAIMS:

1. An apparatus for use in indicating the geographic position of a craft in accordance bearing and distance information from beacon transmitters, said indicating apparatus comprising

a casing;

a figurative point movable according to two orthogenal displacements;

an access slot gaping on three sides of said casing so as to receive a geographical map or portion of a map even when approximately oriented and folded for reception in said gap;

a window placed above said map receiving slot, said figurative point being displaceable in the area of said window in order to occupy any position in the window;

means for alignment with the meridian of said map, constituted by pointers which are brought into coincidence with said meridian;

two associated transducers for supplying signals representing angular position information of said map with respect to said indicating apparatus, this information being a function of the respective positions of said pointers;

means for setting values for basic reference information signals including information on magnetic declination, and scale of said map;

a device for locking said map in position at the back of said window holding it firmly and accepting the folding of said map in several thicknesses, the operation of indicating apparatus being subordinated to the locking of said maps through said locking device.

2. An apparatus as claimed in claim 1 and further comprising:

a glass constituting the rear face of said window which is double-glazed;

a glass constituting the front face of said window;

a pressure-plate forming part of said locking device and immobilizing said map against said rear-face glass;

said figurative point being displaced between the two said glasses and the front face glass being adapted to receive from the user any temporary indication.

3. An apparatus as claimed in claim 1 and further comprising

a wire carrying said movable figurative point, said wire being adapted to be translated by displacement in abscissae in order to obtain a longitude and to be wound and unwound by displacement in ordinates in order to obtain a latitude;

a first chain of components including a first motor, a first wound potentiometer and a translation trolley, and a second chain of components including a second motor, a second wound potentiometer, and a winding and unwinding drum mounted on said trolley, permitting the two displacements of said figurative point,

whereby said two displacements of said figurative point serve, when controlled by the user, for determining either

the position on said map of selected beacon transmitters;

the position on said map of objectives and points on the route;

and said two displacements of said figurative point serve, for determining, at every moment, the exact position on the map of said craft.

4. An apparatus as claimed in claim 1 and further comprising:

a single knob for fixing the value of basic reference information relating to declination;

two simple knurled knobs for the control by the user of said two displacements of said figurative point;

three knurled knobs for fixing the value of basic reference information relating to scale;

push-buttons accompanied by indicators especially for the selection of radio navigation references, including beacon transmitters, objectives and points on the route.

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L5: Entry 6 of 16 File: USPT Mar 9, 1999

DOCUMENT-IDENTIFIER: US 5878977 A
TITLE: Offset detection apparatus and flying object guiding system using the apparatus

Brief Summary Paragraph Right (2):
A conventional flying object guiding system comprises a navigation calculator mounted on the flying object for calculating the information such as the attitude angle and the position of the flying object and an external guiding means for transmitting to the flying object by radio the information on the direction of movement on a reference coordinate system (the combined information on the azimuth and elevation or the information on the target position). The flying object calculates the attitude angle and positional information of the flying object using the navigation calculator and determines the direction and amount of steering on the basis of the information on the direction of movement sent from the guiding means.

Brief Summary Paragraph Right (3):
The conventional flying object guiding system described above shares a coordinate system with the steering system using the attitude angle and the positional information of the flying object obtained from the navigation calculator mounted on the flying object. Specifically, in the case where the guiding system fails to share a coordinate system with the flying object steering system, the flying object cannot fly in the direction conforming with the direction information which may be received from the guiding means. As a result, the guiding system is required to share a coordinate system with the flying object steering system.

Detailed Description Paragraph Right (74):
An explanation will be given of the relation between the middle point C of the sensors, the position of the rotative axis Z of laser beam scanning and the phase difference .DELTA..phi. with reference to FIGS. 12F and 12G.

Detailed Description Paragraph Right (91):
Especially, the flying object can be guided to a target without carrying any navigation calculator for sharing a coordinate system with the guiding means, and therefore the flying object can be reduced in size and weight.

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L5: Entry 9 of 16 File: USPT Feb 17, 1998

DOCUMENT-IDENTIFIER: US 5719500 A
TITLE: Process for detecting metallic items including a search path defined by a linear movement with a superimposed rotational movement along a curved closed path

Brief Summary Paragraph Right (31):
In a preferred embodiment of the invention, a second probe guiding device having at least one search probe is arranged on the first probe guiding device, and can be rotated about an axis, which is essentially perpendicular to the search surface. In this embodiment, which utilizes the above-described "lawn mower principle", one or more search probes can be arranged on a rigid rotation element, such as, for example, an arm-type support or a disk, at a distance to an axis aligned essentially perpendicularly with respect to the floor surface of the vehicle. A motor, advantageously an electric motor, whose rotational speed can easily be controlled, may drive the rotation element by way of transmissions. For example, in the area of the bearing of the rotation element, angle sensors may be provided to record the angular position of the rotation element and transmit it to an analyzing unit. The angle sensors are part of the position determining devices for the search probe. From the radial distance between the search probe and the rotating axis and the rotating position, the position of the search probe relative to the axis of rotation can be determined in polar coordinates. The position of the axis of rotation (or the position of another point which is fixed relative to the axis of rotation) can be determined, as described above, by means of other position sensors devices. As a result, the position of the search probe with respect to the search surface or the search area can be determined at any time. This information may be transmitted to the analyzing devices.

Detailed Description Paragraph Right (1):
Symbolized by broken lines, FIG. 1 shows a square corner portion of a search area 1 on the earth's surface. In the search area, a first probe guiding device 2 (for example, a land vehicle) is moved along a first direction 3. The position of the vehicle 2 in the search area 1 is determined by a differential GPS system 4 which is part of the localizing device of the detection system. The GPS receivers, specifically the stationary receiver 6 and the mobile receiver 7 arranged on the vehicle 2, which are in a signal-transmitting contact with the satellites 5, permit an exact determination of the position of the mobile receiver 7 relative to the stationary receiver 6, even if the absolute coordinates of the receivers 6, 7 are systematically offset from the true coordinates. If desired, the absolute coordinates of the stationary receiver 6 can be measured and used to determine the coordinates of the mobile receiver.

Detailed Description Paragraph Right (9):
By means of the described embodiments, a vehicle-supported and GPS-supported eddy current and magnetometer search system is provided for detecting the location and depth of metallic bodies close to the surface and at greater depth for the purpose of clearing and disposing of old waste.

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L5: Entry 5 of 16 File: USPT May 18, 1999

DOCUMENT-IDENTIFIER: US 5904210 A
TITLE: Apparatus and method for detecting a location and an orientation of an underground boring tool

Detailed Description Paragraph Right (77):
A significant advantage of a geologic imaging antenna configuration 520 of the present invention provides for true three-dimensional imaging of a subsurface as shown in FIG. 20. A pair of antennae, antenna-A 522 and antenna-B 524, are preferably employed in an orthogonal configuration to provide for three-dimensional imaging of a buried hazard 526. Antenna-A 522 is shown as directed along a direction contained within the y-z axis and at .+-.45.degree. relative to the z-axis. Antenna-B 524 is also directed along a direction contained within the y-z plane, but at -45.degree. relative to the z-axis, in a position rotated 90.degree. from that of antenna-A 522. It is noted that the hyperbolic time-position data distribution typically obtained by use of a conventional single-axis antenna, may instead be plotted as a three-dimensional hyperbolic shape that provides width, depth, and length dimensions of a detected buried hazard 526. It is further noted that a buried hazard 526, such as a drainage pipeline, which runs parallel to the survey path 528 will readily be detected by the three-dimensional imaging GPR system. Respective pairs of orthogonally oriented transmitting and receive antennae may be employed in the transmitter 54 and receiver 56 of the PDU 28 in accordance with one embodiment of the invention.

Detailed Description Paragraph Right (95):
In the embodiment illustrated in FIG. 24, a Global Positioning System (GPS) 170 is employed to provide position data for the GRS 150. In accordance with a U.S. Government project to deploy twenty-four communication satellites in three sets of orbits, termed the Global Positioning System (GPS), various signals transmitted from one or more GPS satellites may be used indirectly for purposes of determining positional displacement of a boring tool 24 relative to one or more known reference locations. It is generally understood that the U.S. Government GPS satellite system provides for a reserved, or protected, band and a civilian band. Generally, the protected band provides for high-precision positioning to a classified accuracy. The protected band, however, is generally reserved exclusively for military and other government purposes, and is modulated in such a manner as to render it virtually useless for civilian applications. The civilian band is modulated so as to significantly reduce the accuracy available, typically to the range of one hundred to three hundred feet.

Detailed Description Paragraph Right (96):
The civilian GPS band, however, can be used indirectly in relatively high-accuracy applications by using one or more GPS signals in combination with one or more ground-based reference signal sources. By employing various known signal processing techniques, generally referred to as differential global positioning system (DGPS) signal processing techniques, positional accuracies on the order of centimeters are now achievable. As shown in FIG. 24, the GRS 150 uses the signal produced by at least one GPS satellite 172 in cooperation with signals produced by at least two base transponders 174, although the use of one base transponder 174 may be satisfactory in some applications. Various known methods for exploiting DGPS signals using one or more base transponders 174 together with a GPS satellite 172 signal and a mobile GPS receiver 176 coupled to the control unit 32 may be employed to accurately resolve the boring tool 24 movement relative to the base transponder 174 reference locations using a GPS satellite signal source.

Detailed Description Paragraph Right (101):
Still referring to FIG. 25, accurate mapping of the boring site may be accomplished using a global positioning system 170, range radar system 180 or ultrasonic positioning system 190 as discussed previously with respect to FIG. 24. A mapping system having a GPS system 170 includes first and second base transponders 600 and 602 together with one or more GPS signals 606 and 608 received from GPS satellites 172. A mobile transponder 610, coupled to the control unit 32, is provided for receiving the GPS satellite signal 606 and base transponder signals 612 and 614 respectively transmitted from the transponders 600 and 602 in order to locate the position of the control unit 32. As previously discussed, a modified form of differential GPS positioning techniques may be employed to enhance positioning accuracy to the centimeter range. A second mobile transponder 616, coupled to the PDU 28, is provided for receiving the GPS satellite signal 608 and base transponder signals 618 and 620 respectively transmitted from the transponders 600 and 602 in order to locate the position of the PDU 28.

Detailed Description Paragraph Right (102):
In another embodiment, a ground-based range radar system 180 includes three base transponders 600, 602, and 604 and mobile transponders 610 and 616 coupled to the control unit 32 and PDU 28, respectively. It is noted that a third ground-based transponder 604 may be provided as a backup transponder for a system employing GPS satellite signals 606 and 608 in cases where GPS satellite signal 606 and 608 transmission is temporarily terminated, either purposefully or unintentionally. Position data for the control unit 32 are processed and stored by the GRS 150 using the three reference signals 612, 614, and 622 received from the ground-based transponders 600, 602, and 604, respectively. Position data for the PDU 28, obtained using the three reference signals 618, 620, and 624 received respectively from the ground-based transponders 600, 602, and 604, are processed and stored by the local position locator 616 coupled to the PDU 28 and then sent to the control unit 32 via a data transmission link 34. An embodiment employing an ultrasonic positioning system 190 would similarly employ three base transponders 600, 602, and 604, together with mobile transponders 610 and 616 coupled to the control unit 32 and PDU 28, respectively.

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L9: Entry 19 of 47 File: USPT Aug 1, 1995

DOCUMENT-IDENTIFIER: US 5438517 A
TITLE: Vehicle position determination system and method

Abstract Paragraph Left (1):
Systems and methods allow for the accurate determination of the terrestrial position of an autonomous vehicle in real time. A first position estimate of the vehicle 102 is derived from satellites of a global positioning system and/or a pseudolite(s). The pseudolite(s) may be used exclusively when the satellites are not in the view of the vehicle. A second position estimate is derived from an inertial reference unit and/or a vehicle odometer. The first and second position estimates are combined and filtered using novel techniques to derive a more accurate third position estimate of the vehicle's position. Accordingly, accurate autonomous navigation of the vehicle can be effectuated using the third position estimate.

Brief Summary Paragraph Right (2):
The present invention relates to positioning systems, and more particularly, to a positioning system and method for determining the terrestrial position of an autonomous vehicle on or near the planet Earth's surface.

Brief Summary Paragraph Right (4):
Several national governments, including the United States (U.S.) of America, are presently developing a terrestrial position determination system, referred to generically as a global positioning system (GPS). In a GPS, a number of satellites are placed in orbit around the planet Earth. The GPS satellites are designed to transmit electromagnetic signals. From these electromagnetic signals, the absolute, terrestrial position (position with respect to the Earth's center) of any receiver at or near the Earth's surface can ultimately be determined.

Brief Summary Paragraph Right (5):
The U.S. government has designated its GPS the "NAVSTAR." The NAVSTAR GPS will be declared operational by the U.S. government in 1993. Moreover, the government of the Union of Soviet Socialist Republics (U.S.S.R.) is currently developing a GPS known as "GLONASS," which is substantially similar to the NAVSTAR GPS.

Brief Summary Paragraph Right (6):
In the NAVSTAR GPS, it is envisioned that four orbiting GPS satellites will exist in each of six separate orbits. A total of 24 GPS satellites will be in orbit at any given time with 21 GPS satellites in operation and 3 GPS satellites serving as spares. The three GPS satellite orbits will have mutually orthogonal planes relative to the Earth. The GPS satellite orbits will be neither polar orbits nor equatorial orbits. Moreover, the GPS satellites will orbit the Earth once every 12 hours.

Brief Summary Paragraph Right (7):
Using the NAVSTAR GPS, the relative position of orbiting GPS satellites with respect to any Earth receiver can be determined from the electromagnetic signals. The relative position is commonly referred to as a "pseudorange." Moreover, the relative position can be calculated by two methods.

Brief Summary Paragraph Right (8):
One method is to measure the propagation time delays between transmission and reception of the emanating electromagnetic signals. In the NAVSTAR GPS, the electromagnetic signals are encoded continuously with the time at which the signals

are transmitted from the GPS satellites. Needless to say, one can make note of the reception time and subtract the encoded transmission time in order to derive time delays. From the calculated time delays and from knowing the speed at which electromagnetic waves travel through the atmosphere, pseudoranges can be accurately derived. Pseudoranges computed using the foregoing method are referred to in the context of this document as "actual" pseudoranges.

Brief Summary Paragraph Right (9):
Another method involves satellite position data that is encoded in the electromagnetic signals being transmitted from the orbiting satellites. Almanac data relating to the satellite position data of the NAVSTAR GPS is publicly available. Reference to this almanac data in regard to data encoded in the electromagnetic signals allows for an accurate derivation of pseudoranges. Pseudoranges computed using the foregoing method are referred to in the context of this document as "estimated" pseudoranges.

Brief Summary Paragraph Right (10):
However, with respect to the previous method of deriving estimated pseudoranges, it should be noted that the satellite position data is updated at the GPS satellite only once an hour on the hour. Consequently, an estimated pseudorange decreases in accuracy over time after each hour until the next hour, when a new estimated pseudorange is computed using updated satellite position data.

Brief Summary Paragraph Right (11):
Furthermore, by knowing the relative position of at least three of the orbiting GPS satellites, the absolute terrestrial position (that is, longitude, latitude, and altitude with respect to the Earth's center) of any Earth receiver can be computed via simple geometric theory involving triangulation methods. The accuracy of the terrestrial position estimate depends in part on the number of orbiting GPS satellites that are sampled. Using more GPS satellites in the computation can increase the accuracy of the terrestrial position estimate.

Brief Summary Paragraph Right (12):
Conventionally, four GPS satellites are sampled to determine each terrestrial position estimate because of errors contributed by circuit clock differentials among the Earth receiver and the various GPS satellites. Clock differentials could be several milliseconds. If the Earth receiver's clock were synchronized with that of the GPS satellites, then only three GPS satellites would need to be sampled to pinpoint the location of the Earth receiver.

Brief Summary Paragraph Right (13):
In the NAVSTAR GPS, electromagnetic signals are continuously transmitted from all of the GPS satellites at a single carrier frequency. However, each of the GPS satellites has a different modulation scheme, thereby allowing for differentiation of the signals. In the NAVSTAR GPS, the carrier frequency is modulated using a pseudorandom signal which is unique to each GPS satellite. Consequently, the orbiting GPS satellites in the NAVSTAR GPS can be identified when the carrier frequencies are demodulated.

Brief Summary Paragraph Right (14):
Furthermore, the NAVSTAR GPS envisions two modes of modulating the carrier wave using pseudorandom number (PRN) signals. In one mode, referred to as the "coarse/acquisition" (C/A) mode, the PRN signal is a gold code sequence having a chip rate of 1.023 MHz. The gold code sequence is a well-known conventional pseudorandom sequence in the art. A chip is one individual pulse of the pseudorandom code. The chip rate of a pseudorandom code sequence is the rate at which the chips in the sequence are generated. Consequently, the chip rate is equal to the code repetition rate divided by the number of members in the code. Accordingly, with respect to the coarse/acquisition mode of the NAVSTAR GPS, there exists 1,023 chips in each gold code sequence and the sequence is repeated once every millisecond. Use of the 1.023 MHz gold code sequence from four orbiting GPS satellites enables the terrestrial position of an Earth receiver to be determined to an approximate accuracy of within 60 to 300 meters.

Brief Summary Paragraph Right (15):
The second mode of modulation in the NAVSTAR GPS is commonly referred to as the

"precise" or "protected" (P) mode. In the P mode, the pseudorandom code has a chip rate of 10.23 MHz. Moreover, the P mode sequences are extremely long, so that the sequences repeat no more than once every 267 days. As a result, the terrestrial position of any Earth receiver can be determined to within an approximate accuracy of 16 to 30 meters.

Brief Summary Paragraph Right (17):
In order for the Earth receivers to differentiate the various C/A signals from the different orbiting GPS satellites, the Earth receivers usually include a plurality of different gold code sources for locally generating gold code sequences. Each locally-derived gold code sequence corresponds with each unique gold code sequence from each of the GPS satellites.

Brief Summary Paragraph Right (18):
The locally-derived gold code sequences and the transmitted gold code sequences are cross correlated with each other over gold code sequence intervals of one millisecond. The phase of the locally-derived gold code sequences vary on a chip-by-chip basis, and then within a chip, until the maximum cross correlation function is obtained. Because the cross correlation for two gold code sequences having a length of 1,023 bits is approximately 16 times as great as the cross correlation function of any of the other combinations of gold code sequences, it is relatively easy to lock the locally derived gold code sequence onto the same gold code sequence that was transmitted by one of the GPS satellites.

Brief Summary Paragraph Right (19):
The gold code sequences from at least four of the GPS satellites in the field of view of an Earth receiver are separated in this manner by using a single channel that is sequentially responsive to each of the locally-derived gold code sequences, or alternatively, by using parallel channels that are simultaneously responsive to the different gold code sequences. After four locally-derived gold code sequences are locked in phase with the gold code sequences received from four GPS satellites in the field of view of the Earth receiver, the relative position of the Earth receiver can be determined to an accuracy of approximately 60 to 300 meters.

Brief Summary Paragraph Right (20):
The foregoing approximate accuracy of the NAVSTAR GPS is affected by (1) the number of GPS satellites transmitting signals to which the Earth receiver is effectively responsive, (2) the variable amplitudes of the received signals, and (3) the magnitude of the cross correlation peaks between the received signals from the different GPS satellites.

Brief Summary Paragraph Right (23):
In addition to the GPS, it is known in the conventional art to use inertial systems in navigation systems to obtain position estimates of vehicles. Such an inertial reference unit (IRU) obtains specific-force measurements from accelerometers in a reference coordinate frame which is stabilized by gyroscopes, or gyros. An IRU can be of several types, including for example, laser, mechanical, or fiber optic. In an unaided navigation system using an IRU, the specific force (corrected for the effects of the Earth's gravity) as measured by an accelerometer is integrated into a navigation mathematical equation to produce the vehicle's position and velocity.

Brief Summary Paragraph Right (24):
The instrument measurements of the IRU may be specified in a different rectangular coordinate frame than the reference navigation frame, depending on the platform implementation. The most commonly used reference navigation frame for near Earth navigation is the local-level frame (east-north-vertical). Several gimballed platform implementations exist with the forgoing reference navigation frame.

Brief Summary Paragraph Right (25):
In a gimballed, local level-north seeking IRU, the gyroscopes and accelerometers are mounted on a platform which is torqued to maintain the platform level and azimuth pointing to the north. The platform is the reference plane. In contrast, in a gimballed, local-level azimuth-wander IRU, the platform is maintained level, but is not torqued about the vertical axis.

Brief Summary Paragraph Right (26):
Furthermore, in a strap-down IRU, the gyroscopes and the accelerometers are directly mounted on the vehicle body. They measure the linear and angular motion of the vehicle relative to inertial space. The motion is expressed in vehicle coordinates. Therefore, in a strap-down IRU, it is necessary to first compute the altitude of the vehicle to the referenced navigation frame. Then, the computed altitude is used to transform the accelerometer measurements into the reference frame. After the accelerometer data of a strap-down IRU has been extrapolated into the reference frame, the solution of the navigation equations mentioned previously is identical in both the gimballed IRU and the strap-down IRU.

Brief Summary Paragraph Right (29):
The performance of navigation systems using IRUs is primarily limited by errors contributed by the various constituent sensors within the IRUs. Gyroscopes drift. Accelerometers have inherent biases. Further, errors are contributed from improper scale factors and improper IRU alignment angles. Typically, the preceding errors cause inaccuracies in the estimates of vehicle positions, velocity, and altitude, which accumulate over time as a vehicle mission progresses. To some extent, the errors are dependent on user dynamics.

Brief Summary Paragraph Right (30):
If a very accurate navigation system is required for a vehicle, high precision gyroscopes and accelerometers can be utilized to satisfy that need. However, such high precision equipment increase the complexity and costs of the vehicle.

Brief Summary Paragraph Right (31):
Autonomous vehicle navigation is also known in the conventional art. "Autonomous" means unmanned or machine controlled. However, the autonomous systems known in the art are rudimentary at best.

Brief Summary Paragraph Right (32):
Autonomous systems exist which rely on positioning based on visual sensing. For instance, vision-based positioning is used in the Martin Marietta Autonomous Land Vehicle, as described in "Obstacle Avoidance Perception Processing for the Autonomous Land Vehicle," by R. Terry Dunlay, IEEE, CH2555-1/88/0000/0912$01.00, 1988.

Brief Summary Paragraph Right (33):
Some of the vision-based positioning systems use fixed guide lines or markings on a factory floor, for example, to navigate from point to point. Other positioning systems involve pattern recognition by complex hardware and software. Still other systems, known as "dead-reckoning" systems, navigate by keeping track of the vehicle's position relative to a known starting point. This tracking is performed by measuring the distance the vehicle has travelled and monitoring the vehicle direction from the starting point. The preceding autonomous navigation systems suffer from numerous drawbacks and limitations. For instance, if a navigation system on a vehicle fails to recognize where the vehicle is located, or looses track of where the vehicle has been, or miscalculates the vehicle's starting point, then the navigation system will be unable to accurately direct the vehicle to reach its ultimate destination.

Brief Summary Paragraph Right (34):
Moreover, because errors in position estimates of vehicles have a tendency to accumulate over time in the conventional autonomous navigation systems, the navigation systems require frequent and time-consuming initializations. Finally, conventional navigation systems require placement of patterns and markers along vehicle routes. This placement of patterns and markers is also time consuming and costly, as well as limits the applicability of these navigation systems to small, controlled areas.

Brief Summary Paragraph Right (35):
The present invention is a vehicle positioning system which, as used throughout, means apparatus, method, or a combination of both apparatus and method. The present invention overcomes many of the limitations of conventional technology in the art of vehicle position determination.

Brief Summary Paragraph Right (36):
The present invention can be used to aid any navigation system for autonomous

vehicles. The autonomous vehicles can be stationary or moving. Moreover, the autonomous vehicles can be at or near the Earth's surface. In other words, the present invention provides for highly accurate and fast tracking of any terrestrial vehicle.

Brief Summary Paragraph Right (37):
The present invention envisions combining and greatly enhancing the conventional capabilities of an IRU and a GPS in a cost-effective manner to provide extremely accurate position estimates of terrestrial vehicles. In doing so, the present invention uses many novel and inventive systems, including apparatuses and methods, which allow for a superior positioning capability and, consequently, a flexible autonomous navigational capability.

Brief Summary Paragraph Right (38):
The present invention further envisions a novel and enhanced combination of three independent subsystems to determine position estimates of vehicles on or near the Earth's surface. One subsystem is a first positioning system using a GPS, for example, the NAVSTAR GPS. The first positioning system computes a first position estimate of a vehicle. Another subsystem is a second positioning system using an IRU and a vehicle odometer. The second positioning system computes a second position estimate. The final subsystem is a processing system for computing the more accurate, third position estimate of the vehicle based upon the first and second position estimates from the previous two subsystems.

Brief Summary Paragraph Right (39):
The present invention envisions a constellation effects method. The constellation effects method provides for selecting the optimal satellite constellation from a larger group of GPS satellites in view of a vehicle to thereby increase the accuracy of first position estimates derived from a GPS.

Brief Summary Paragraph Right (40):
The present invention increases the accuracy of vehicle position estimates by providing differential correction techniques/methods which compensate for noise and errors in positioning data obtained from a GPS and/or an IRU. In the preferred embodiment, a base station serving as a reference point can perform the differential correction techniques/methods and can then relay the obtained data to a vehicle. The vehicle can then use the data received from the base station to enhance the accuracy of the position estimates of the vehicle.

Brief Summary Paragraph Right (41):
The present invention envisions a parabolic bias technique for increasing the accuracy of GPS data received from GPS satellites. A parabolic bias is derived for each GPS satellite to enhance actual pseudoranges for that GPS satellite. In the parabolic bias technique, parabolic models are constructed for the actual pseudoranges and the parabolic biases are extrapolated from the parabolic models.

Brief Summary Paragraph Right (42):
The present invention envisions a base residuals bias technique for increasing the accuracy of GPS data received from GPS satellites. A base residuals bias is derived for modifying first position estimates from the VPS on a vehicle. A base residuals bias is a spatial bias which is the effective difference in the known position of the base station and its estimated position.

Brief Summary Paragraph Right (43):
The present invention includes a novel satellite position predictor method. This method allows the present invention to predict the future positions of GPS satellites. As a result, the accuracy and performance of the positioning system is further enhanced.

Brief Summary Paragraph Right (44):
The present invention includes a weighted path history technique for increasing the accuracy of first position estimates ultimately derived from a GPS. The weighted path history technique uses previous first position estimates to derive a vehicle path model for testing the validity of future first position estimates. Use of the weighted path history technique results in a reduction to wandering of first position estimates and in enhanced immunities to spurious position computations.

Brief Summary Paragraph Right (45):
The present invention further provides for anti-selective availability of data received from GPS satellites of any GPS. An anti-selective availability technique detects and corrects false positioning data received from any GPS. False data could be received from the NAVSTAR GPS or the GLONASS GPS (1) because of intentional tainting by the respective governments of the U.S. and U.S.S.R. or (2) because of technical malfunctions.

Drawing Description Paragraph Right (3):
FIG. 1A is a high level block diagram 100A of the operational GPS satellites in the NAVSTAR GPS, which comprises 21 operational GPS satellites 130-170 distributed in 6 orbital planes 174-184 and 3 spare GPS satellites (not shown);

Drawing Description Paragraph Right (4):
FIG. 2 is a diagrammatic illustration of four GPS satellites;

Drawing Description Paragraph Right (5):
FIG. 2A illustrates four, simultaneous, navigation equations regarding four GPS satellites 200-206 of the NAVSTAR GPS, which equations include the clock bias C.sub.b between the GPS satellites 200-206 and the vehicle 102;

Drawing Description Paragraph Right (7):
FIG. 4 is a high level block diagram 400 of the interrelationships between a navigator 406, a vehicle VPS architecture 1000, and vehicle controls 408 of the present invention;

Drawing Description Paragraph Right (9):
FIG. 6 is a high level block diagram 600 of the operation of a GPS, possibly the NAVSTAR GPS, which includes a GPS satellite constellation 200, 202, 204, and 206 and which is used in conjunction with a pseudolite 105 and a base station 188 to accurately determine the position of a vehicle 102;

Drawing Description Paragraph Right (10):
FIG. 7 is a low level block diagram showing the electrical architecture/hardware 700 of a GPS processing system of the preferred embodiment;

Drawing Description Paragraph Right (11):
FIG. 8 is a low level flow diagram 800 illustrating the functioning of software in the GPS processing system 700, as shown in FIG. 7, of the preferred embodiment;

Drawing Description Paragraph Right (18):
FIG. 14 is a polar plot 1400 on a coordinate system 1402 illustrating a set of computed estimated pseudoranges 1404, 1406, 1408, and 1410 pertaining to a GPS satellite constellation of four GPS satellites (not shown), wherein a shaded region 1412 shows the possible position estimate of a vehicle when the GPS satellites (not shown) giving rise to pseudoranges 1406 and 1408 are consulted;

Drawing Description Paragraph Right (25):
FIG. 20 is a high level graphical representation 2000 of first position estimates of the vehicle 102 wherein the weighted path history method illustrated in FIG. 19 would eliminate a first position estimate 2010 because of its extreme inconsistency with the vehicle path;

Drawing Description Paragraph Right (28):
FIG. 22 is a diagram 2200 of vehicle route definitions using nodes and segments according to the present invention;

Drawing Description Paragraph Right (40):
FIG. 34 is a diagram 3400 showing how an error vector including curvature is computed with the vehicle path included;

Drawing Description Paragraph Right (44):
FIG. 38A is an illustration 3800B of a vehicle mounted scanner 404;

Drawing Description Paragraph Right (45):
FIG. 38B is an illustration 3800B of an autonomous vehicle scanning 102 for an obstacle 4002;

Drawing Description Paragraph Right (47):
FIG. 40 is a diagram 4000 of an autonomous vehicle 102 avoiding obstacles 4002;

Drawing Description Paragraph Right (50):
FIG. 43 is a an intermediate level block diagram 4300 of a control system for an autonomous mining vehicle of the present invention;

Drawing Description Paragraph Right (58):
FIG. 51 is a high level block diagram 5100 of a tricycle steering model used to develop a navigation system of the present invention;

Detailed Description Paragraph Right (2):
(1) "Absolute position" in the context of this document refers to a position relative to the center of the Earth. Generally, an absolute position will be in reference to a vehicle or the base station, both on or near the Earth's surface. First, second, and third position estimates are all absolute positions in the preferred embodiment of the present invention.

Detailed Description Paragraph Right (3):
(2) "Actual pseudorange" means an approximation of the distance between (1) a reference point and (2) a source of a terrestrial position determination system. In this document, actual pseudoranges usually refers to an approximation of the distance between (1) an Earth receiver and (2) GPS satellites and/or pseudolites. Actual pseudoranges are approximated by first measuring the propagation time delays between transmission and reception of the electromagnetic signals emanated from the GPS satellites and/or pseudolites. Actual pseudoranges can be readily calculated by multiplying the calculated time delays by the speed of light, or 2.9979245898 * 10.sup.8 m/s.

Detailed Description Paragraph Right (4):
(3) "Anti-selective availability" refers to a method/technique/process for detecting and compensating for corrupted GPS data in the coarse/acquisition (C/A) mode of modulation.

Detailed Description Paragraph Right (5):
(4) "Autonomous" is used in this document in its conventional sense. It indicates operation which is either completely automatic or substantially automatic or without significant human involvement in the operation. Generally, an autonomous vehicle means an unmanned vehicle in operation, or a vehicle in operation without a human pilot or co-pilot. However, an autonomous vehicle may be driven or otherwise operated automatically and also have a human passenger(s) as well.

Detailed Description Paragraph Right (8):
(7) "Base estimated position" or "BEP" refers to the relative position of the base station with respect to a vehicle. The BEP is used in the base correlator bias technique of Part II.F.2.d. of this document.

Detailed Description Paragraph Right (10):
(9) "Base position estimate" means the absolute position estimate of the base station as derived from the GPS processing system within the host processing system. The base position estimate is substantially similar to the first position estimate derived by the GPS processing system at the vehicle. The base position estimate is computed in the base residuals bias technique at Part II.F.2.c. of this document.

Detailed Description Paragraph Right (14):
(13) "Clock bias" means the difference in the clock times between (1) the transmission circuitry of GPS satellites and/or pseudolites and (2) the reception circuitry of an Earth receiver. When using a clock bias in the computation of a spatial bias, the clock bias is multiplied by the speed of light, or 2.998 * 10.sup.8 meters per second. Consequently, the clock bias is transformed into units of length.

Detailed Description Paragraph Right (15):
(14) "Constellation" refers to a group comprised of GPS satellites and/or pseudolites whose signals are utilized to derive an absolute position estimate of a point on or near the Earth's surface. See "optimal constellation" below.

Detailed Description Paragraph Right (16):
(15) "Constellation effects method" means a technique or process by which an optimal constellation of GPS satellites is selected from a larger group of GPS satellites in view of a vehicle.

Detailed Description Paragraph Right (18):
(17) "Earth receiver" refers to any apparatus or device, or any part thereof, which receives and processes signals from a GPS and/or pseudolites. Earth receivers may be situated on or near the Earth's surface. Moreover, earth receivers may take the form of, for example, a vehicle or a base station.

Detailed Description Paragraph Right (19):
(18) "Estimated pseudorange" refers to an approximation of the distance between (1) a reference point and (2) a source of a terrestrial position determination system. In this document, actual pseudoranges usually refers to an approximation of the distance between (1) an Earth receiver and (2) GPS satellites and/or pseudolites. Estimated pseudoranges are computed from GPS data encoded on the electromagnetic signals being transmitted from the GPS satellites and/or the pseudolites. Almanac equations for computing estimated pseudoranges from the GPS data of the NAVSTAR GPS are publicly available.

Detailed Description Paragraph Right (20):
(19) "First position estimate" or "FPE" or "FPE(i)" refers to an estimated absolute position of any vehicle which is outputted, in any form, from the GPS. The first position estimate and a second position estimate are independently derived in the present invention. Subsequently, these estimates are combined and filtered to derive a third position estimate. Consequently, the accuracy of the first position estimate affects the accuracy of the third position estimate.

Detailed Description Paragraph Right (21):
(20) "GLONASS GPS" refers to the GPS which has been designed and which is currently being deployed by the U.S.S.R.

Detailed Description Paragraph Right (22):
(21) "Global positioning system" or "GPS" is a type of terrestrial position determination system. In a GPS, a number of satellites are placed in orbit around the planet Earth. The GPS satellites are designed to transmit electromagnetic signals. From these electromagnetic signals, the absolute, terrestrial position (position with respect to the Earth's center) of any receiver at or near the Earth's surface can ultimately be determined. The U.S. government has designated its GPS the "NAVSTAR." The government of the U.S.S.R. has designated its GPS the "GLONASS."

Detailed Description Paragraph Right (23):
(22) "GPS data" means all data encoded on signals transmitted from GPS satellites of a GPS. GPS data includes, for example, ephemeris data and time data.

Detailed Description Paragraph Right (24):
(23) "GPS processing system" refers to the system of the present invention for receiving signals from a terrestrial position determination system and for deriving first position estimates of vehicles from the received signals. In the preferred embodiment, the GPS processing system receives electromagnetic signals from GPS satellites of a GPS and/or from pseudolites.

Detailed Description Paragraph Right (25):
(24) "Host processing system" refers to a computer system which is operating at the base station for performing methods and techniques which increase the accuracy of position estimates of vehicles. Data derived from these methods and techniques is transmitted to vehicles so that the vehicles can use the data when computing first, second, and third position estimates. In the preferred embodiment, the architecture/hardware of the host processing system is substantially similar to the

architecture/hardware of the VPS.

Detailed Description Paragraph Right (26):
(25) "Inertial reference unit" or "IRU" refers to a system, usually on-board a vehicle, for aiding in the derivation of a second position estimate of the vehicle. An IRU obtains specific-force measurements from accelerometers in a reference coordinate frame which is stabilized by gyroscopes, or gyros. An IRU can be of a laser type or a mechanical type. In an unaided navigation system using an IRU, the specific force (corrected for the effects of the Earth's gravity) as measured by an accelerometer is integrated into a navigation mathematical equation to produce the vehicle's position and velocity. In the preferred embodiment, the IRU is part of the MPS.

Detailed Description Paragraph Right (27):
(26) "Kalman filter" is used in its conventional sense. It refers to a software program for filtering out noise or errors in data. In the preferred embodiment, a GPS Kalman filter is utilized to filter out noise or errors in the GPS processing system in order to enhance the accuracy of first position estimates. Also, a VPS Kalman filter is utilized to filter out noise in the VPS in order to enhance the accuracy of second position estimates.

Detailed Description Paragraph Right (28):
(27) "Motion positioning system" or "MPS" means a system comprising at least an IRU and a vehicle odometer. In the preferred embodiment, the MPS derives the second position estimate of any vehicle on or near the Earth's surface. Moreover, an MPS need not be present at the base station due to its stationary nature.

Detailed Description Paragraph Right (29):
(28) "Optimal constellation" means a satellite constellation in which the relative positions of the GPS satellites in space affords superior triangulation capabilities in order to derive the most accurate estimate of a point on or near the Earth's surface.

Detailed Description Paragraph Right (32):
(31) "NAVSTAR GPS" means the GPS which has been designed and which is currently being deployed by the U.S. government.

Detailed Description Paragraph Right (33):
(32) "Navigation system" refers to any systems and/or methods for guiding any vehicle on or near the Earth's surface. The navigation system can be on-board a vehicle. The VPS of the present invention can supply the navigation system of the vehicle with a very accurate, third position estimate of the vehicle so that the navigation system can thereby precisely guide the vehicle.

Detailed Description Paragraph Right (34):
(33) "Parabolic bias" is a spatial bias computed by constructing parabolic models for the actual pseudoranges of each observed GPS satellite and extrapolating values from the parabolic models. In the preferred embodiment, the parabolic biases are the actual pseudoranges minus the value extrapolated from the constructed parabolic models and minus the clock biases (in units of length, via multiplying by the speed of light).

Detailed Description Paragraph Right (35):
(34) "Parabolic bias technique" is a method for computing parabolic biases for each of the GPS satellites that are utilized.

Detailed Description Paragraph Right (37):
(36) "Pseudolite" refers to a radiating system on or near the Earth's surface for emulating a GPS satellite. In the preferred embodiment, electromagnetic signals, similar to those from GPS satellites, are transmitted from land-based pseudolites. One or more pseudolites can be used to emulate GPS satellites to enhance the computation of first position estimates.

Detailed Description Paragraph Right (38):
(37) "Pseudolite data" means all data encoded on signals received from pseudolites. Pseudolite data resembles GPS data in many respects and includes similar information.

Detailed Description Paragraph Right (39):
(38) "Pseudorange" means the distance between a source of a terrestrial position determination system and a point on or near the Earth's surface. In the preferred embodiment, sources can be GPS satellites and/or pseudolites. The terrestrial position determination system can be a GPS used with pseudolites, if any. Further, the point on or near the Earth's surface can be the base station and/or vehicles.

Detailed Description Paragraph Right (40):
(39) "Satellite position predictor" is a method for determining the future positions of GPS satellites. The method allows for the selection of optimal constellations ahead of time.

Detailed Description Paragraph Right (41):
(40) "Second position estimate" or "SPE" refers to an estimated absolute position of any vehicle which is outputted, in any form, from the MPS. Second position estimates include at least position information from an IRU. The second position estimate could include position information from a vehicle odometer situated on a vehicle.

Detailed Description Paragraph Right (45):
(44) "Terrestrial position determination system" means any position determination system which can be used to ultimately estimate the terrestrial position of an Earth receiver. The signals may be in the form of, for example, electromagnetic waves, percussion waves, and/or sound waves. In the preferred embodiment, the terrestrial position determination system is the NAVSTAR GPS.

Detailed Description Paragraph Right (46):
(45) "Third position estimate" or "TPE" refers an estimated absolute position of any vehicle that is outputted, in any form, from the VPS. Third position estimates are more accurate position estimates of vehicle positions than the first and second position estimates. Third position are derived by the VPS processing system from the first and second position estimates.

Detailed Description Paragraph Right (47):
(46) "Vehicle" means any carrier for the transportation of physical things. Vehicles may take the form of mining trucks, construction trucks, farm tractors, automobiles, ships, boats, trains, balloons, missiles, or aircraft. In the preferred embodiment, a Caterpillar Inc. 785 off-highway truck is utilized.

Detailed Description Paragraph Right (48):
(47) "Vehicle positioning system" or "VPS" refers to the system of the present invention for deriving position estimates of any vehicle. The position estimates from the VPS are extremely accurate and can be used by a navigation system on any vehicle to accurately guide the vehicle. In the preferred embodiment, position estimates from the VPS are referred to as third position estimates.

Detailed Description Paragraph Right (50):
(49) "Weighted combiner" refers to a particular software program which processes data. Inputted data is assigned a predetermined weighing factor based on the estimated accuracy of the data and the technique used to gather the data. For example, in the preferred embodiment, the first position estimate of the GPS signal 716 is weighted heavier than the second position estimate of the IRU signal 910 because the former is inherently more accurate. Furthermore, the velocity measured by the IRU can be weighted heavier than the velocity measured by the GPS processing system because the former is more accurate. In the preferred embodiment, the velocity measured by the GPS processing system is not used at all, but could be used in other implementations.

Detailed Description Paragraph Right (51):
(50) "Weighted path history technique" is a method or process for increasing the accuracy of first position estimates outputted from the GPS processing system. The technique uses previous first position estimates to derive a vehicle path model for testing the validity of future first position estimates. Use of the weighted path history technique results in a reduction to wandering of first position estimates and in enhanced immunities to spurious position computations.

Detailed Description Paragraph Right (52):

FIG. 1 illustrates a high level block diagram 100 of the preferred embodiment of the present invention. To provide for the accurate autonomous operation of a vehicle 102 on or near the Earth's surface, the present invention includes both a vehicle positioning system (VPS) 1000 and a navigation system 1022. Both of these systems include apparatus, methods, and techniques which, when integrated together, provide for highly accurate control of unmanned vehicles.

Detailed Description Paragraph Right (53):
A. Vehicle Positioning System (VPS)

Detailed Description Paragraph Right (54):
The task of guiding the autonomous vehicle 102 along a prescribed path requires, among other things, an accurate estimate of the vehicle's current position relative to some reference point. Once the current position is known, the vehicle 102 can be commanded to proceed to its next destination.

Detailed Description Paragraph Right (55):
Using the VPS 1000 of the present invention, position estimates of the vehicle 102 can be determined with extreme preciseness. The VPS 1000 receives GPS data from GPS satellites 104 of a GPS, such as the NAVSTAR GPS or the GLONASS GPS.

Detailed Description Paragraph Right (56):
In the preferred embodiment, the NAVSTAR GPS is utilized. FIG. 1A illustrates the NAVSTAR GPS. GPS satellites 130-168 travel around the Earth 172 in six orbits 174-184.

Detailed Description Paragraph Right (57):
Referring back to FIG. 1, the VPS 1000 also may receive pseudolite data from a pseudolite(s) 105. The term "pseudolite" in the context of this document means a radiating device on or near the Earth's surface for emulating a GPS satellite.

Detailed Description Paragraph Right (58):
From the GPS data and/or the pseudolite data, the VPS 1000 derives accurate estimates of position of the vehicle 102. The GPS data and/or the pseudolite data is significantly enhanced via numerous inventive techniques and methods of the present invention to enhance the accuracy of vehicle position estimates.

Detailed Description Paragraph Right (59):
More specifically, the VPS 1000 of the preferred embodiment is a positioning system based on the incorporation of GPS data from the NAVSTAR GPS 104 and from a motion positioning system 900. In the preferred embodiment, the motion positioning system 900 comprises an inertial reference unit (IRU) 904 and/or a vehicle odometer 902. The IRU 904 comprises a laser gyroscope(s) 106 and an accelerometer(s) 108 which can be used to produce position, velocity, roll, pitch and yaw data. The vehicle odometer 902 produces data on the distance travelled by the vehicle 102.

Detailed Description Paragraph Right (60):
A first position estimate of the vehicle 102 is derived by the GPS processing system 700 from GPS data received from the GPS satellites 104 and from the pseudolite data received from the pseudolite(s) 105. To increase the accuracy of the first position estimate the present invention implements a number of methods discussed in detail below. In addition, a second position estimate is derived by the MPS intercommunications processor 906 of the motion positioning system 900, which comprises the IRU 904 and/or the vehicle odometer 902.

Detailed Description Paragraph Right (62):
B. Navigation System

Detailed Description Paragraph Right (63):
The navigation system 1022 receives the third position estimate from the VPS 1000. The navigation system 1022 uses the precise, third position estimate to accurately navigate the vehicle 102. A primary purpose of the navigation system 1022 is to guide the vehicle 102 between points along pre-established or dynamically-generated paths.

Detailed Description Paragraph Right (64):

In the preferred embodiment, the navigation system 1022 is situated on the vehicle 102 itself. In other words, it is essentially an "on-board" system. Moreover, the navigation system 1022 may be designed to be retro-fitted into the vehicle 102.

Detailed Description Paragraph Right (65):
So that the navigation system 1022 can guide the vehicle 102 to follow the pre-established or dynamically-generated paths, various models or conceptual representations are generated and utilized. For example, lines and arcs may be used to establish vehicle paths between objective points. Mathematical B-splines or clothoid curves may be used to model the actual path where the vehicle 102 is to navigate. These mathematical curves will be discussed in detail later in this document.

Detailed Description Paragraph Right (66):
Using the above modelling or representational techniques provides for enhanced data communications, storage, and handling of the vehicle 102. The techniques further allow for simplification of supervisory tasks by providing a hierarchy of control and communication. The higher that a level of control exists on the hierarchical control scheme, the simpler the task and the more compact the commands.

Detailed Description Paragraph Right (67):
The navigation system 1022 further provides for controlling the vehicle's mechanical systems, such as brakes, steering, and engine and transmission, to effect the necessary physical acts required to move, stop, and steer the vehicle 102.

Detailed Description Paragraph Right (68):
The navigation system 1022 also checks the actual position of the vehicle 102 against the desired position to correct vehicle control in accord with the desired position. The navigation system 1022 may run multi-state models to enhance this checking capability. The navigation system 1022 also checks for errors or failures in the system itself and vehicle components. If errors or failures are detected, the navigation system 1022 can provide for fail-safe shutdown by bringing the vehicle 102 to a complete stop.

Detailed Description Paragraph Right (69):
The navigation system 1022 further provides for different modes of controlling the vehicle 102. These include (1) a fully autonomous mode, where navigation of the vehicle 102 is automatically handled by the navigation system 1022; (2) a tele or remote control mode, where a remote human operator (not shown) may control the direction and motion, and so on, of the vehicle 102; and (3) a manual mode, where a human operator sitting in the vehicle 102 can take control of the vehicle 102 and drive it manually.

Detailed Description Paragraph Right (70):
In the autonomous mode, obstacle detection is critical because if the vehicle 102 is not under control, then it could cause great damage to property and great injury to life. The navigation system 1022 can efficiently detect obstacles. Boulders, animals, people, trees, or other obstructions may enter the path of the vehicle 102 unexpectedly. The navigation system 102 is capable of detecting these obstacles, either stopping or plotting a path around the obstruction, and returning the vehicle 102 to its original route when the route is deemed safe.

Detailed Description Paragraph Right (71):
Accurately tracking the desired route is another function of the navigation system 1022. The functioning and architecture of the navigation system 1022 has been designed for real time tracking of vehicle paths at speeds of up to approximately 30 miles per hour (mph).

Detailed Description Paragraph Right (73):
The present invention can comprise a host processing system 186 at a base station 188. The host processing system 186 performs functions for both the VPS 1000 and the navigation system 1022.

Detailed Description Paragraph Right (74):
With respect to the VPS 1000, the host processing system 186 receives GPS data and/or pseudolite data, as shown by respective arrows 190 and 192. In effect, the host

processing system 186 as well as the base station 188 can serve as a known reference point to improve the accuracy of vehicle position estimates as discussed in detail below.

Detailed Description Paragraph Right (75):
The host processing system 186 implements a number of methods for increasing the accuracy of vehicle position estimates. The satellite position predictor method 1800 (Part II.G.) discussed above is also implemented by the host processing system 186. The host processing system 186 will recognize the same satellite constellation that is observed by the vehicle 102.

Detailed Description Paragraph Right (76):
Calculations are performed on the GPS data and/or pseudolite data to derive biases. The term "bias" in the context of this document refers to a differential between two measurements, usually position estimates (spatial bias) or clock rates (clock bias). Because one measurement is usually known to be more accurate than another, the bias is oftentimes referred to as an "error."

Detailed Description Paragraph Right (78):
The foregoing differential correction techniques compensate for data errors. In other words, the biases computed at the host processing system 186 are indicative of data errors. As shown by an arrow 194, the biases are transmitted to the GPS processing system 700 of the vehicle 102. The GPS processing system 700 uses these biases to eliminate errors in vehicle position estimates.

Detailed Description Paragraph Right (79):
The host processing system 186 further provides functions relating to the navigation system 1022 of the present invention. The host processing system 186 serves as the highest level of control of the navigation system 1022, as indicated by an arrow 196. It handles scheduling and dispatching of the vehicle 102 with much the same results as a human dispatcher would achieve. Consequently, the host processing system 186 can thereby determine the work cycle of the vehicle 102.

Detailed Description Paragraph Right (80):
The host processing system 186 commands the vehicle 102 to proceed from a current position to a future position via a specified route, so that the vehicle 102 may accomplish its work goals. The host processing system 186 can specify the vehicle routes by name, rather than by listing each point along the route, as is the case conventionally. Accordingly, the vehicle's on-board navigation system 1022 looks up the named vehicle route and translates the named vehicle route into sets of nodes and segments along the named vehicle route.

Detailed Description Paragraph Right (82):
The following discussion relative to the VPS 1000 will make specific reference to FIGS. 7 through 21. FIGS. 10 and 11 show the architecture/hardware of the VPS 1000. The VPS 1000 is a highly accurate position determination system for a moving or stationary vehicle 102 on or near the Earth's surface.

Detailed Description Paragraph Right (83):
Recall that the VPS 1000 includes the GPS processing system 700 and the MPS 900, which are shown in respective FIGS. 7 and 9. Further recall that the MPS 900 includes the IRU 904 and the vehicle odometer 902, which are both shown in FIG. 9. In effect, these systems have been enhanced and integrated by the present invention to produce a highly effective position determining system.

Detailed Description Paragraph Right (84):
Referring to FIG. 7, the GPS processing system 700 includes an antenna 702 connected to a GPS receiver 706. When the GPS satellites 104 in view of antenna 702 comprise multiple GPS satellites 200-206 as shown in FIGS. 2 and 3, the GPS receiver 706 reads each of their GPS data along with any pseudolite data from any pseudolite(s) 105 in view of antenna 702. In the preferred embodiment, the GPS receiver 706 is responsible for computing the first position estimate of the vehicle 102 from the GPS data and/or the pseudolite data.

Detailed Description Paragraph Right (85):

To increase the accuracy of the first position method, a satellite position predictor method 1800 (Part II.G.) is implemented by a GPS processor 710 of the GPS processing system 700. The satellite position predictor method 1800 predicts the position of any GPS satellite at the current time or any future time.

Detailed Description Paragraph Right (86):
Using the satellite position information, the GPS processing system 700 can determine the optimum GPS satellite constellation to recognize by using a constellation effects method 1300 (Part II.F.). The constellation effects method 1300 is also implemented by the GPS processor 710 in the preferred embodiment. Pursuant to the constellation effects method 1300, a best constellation is selected from the data sources comprising the GPS satellites 200-206 and pseudolite(s) 105.

Detailed Description Paragraph Right (87):
The GPS processor 706 computes a first position estimate of the vehicle 102 based on the best constellation and geometry/triangulation methods. The accuracy of the first position estimate is, in part, dependent on the number of GPS satellites used in the computation. Each additional GPS satellite used can increase the accuracy of the first position estimate. After the computation, the first position estimate of the vehicle 102 is transmitted to a VPS main processor 1002 of FIG. 10.

Detailed Description Paragraph Right (88):
Referring to FIG. 9, the IRU 904 comprises laser gyroscopes and accelerometers which produce position, velocity, roll, pitch, and yaw data. The IRU 904 combines this information into a second position estimate of the vehicle 102. The odometer 902 can be implemented to measure the distance traveled by the vehicle 102. The data from the IRU 904 and the odometer 902 is also transmitted via the MPS intercommunications processor 906 to the VPS main processor 1002, as shown in FIG. 10.

Detailed Description Paragraph Right (89):
The VPS main processor 1002 combines the second position estimate from the MPS 900 (the IRU 904 and perhaps the odometer 902) with the first position estimate from the GPS processing system 700 to produce a more accurate third position estimate.

Detailed Description Paragraph Right (90):
The VPS 1000 further implements a method of eliminating erratic or spurious, third position estimates which can cause vehicle "wandering." This method is called the weighted path history method (Part II.H.). Essentially, the path history of the vehicle 102 is used to statistically determine the accuracy of future estimates of the vehicle 102's position.

Detailed Description Paragraph Right (91):
Referring now to FIGS. 1 and 3, a base station 188 provides a geographic proximate reference point for the VPS 1000. The base station 188 includes a host processing system 186. In the preferred embodiment, the host processing system 186 comprises similar a similar architecture and performs the same functions as the GPS processing system 700. However, the host processing system 700 performs additional functions for increasing the accuracy of first position estimates.

Detailed Description Paragraph Right (92):
The satellite position predictor method 1800 (Part II.G.) is implemented by the host processing system 186, in addition to the GPS processing system 700 as discussed above. Accordingly, the host processing system 186 will recognize the same GPS satellite constellation that is observed by the vehicle 102 or include the same GPS satellite in a larger constellation.

Detailed Description Paragraph Right (93):
Calculations are performed on the GPS data and/or pseudolite data to derive biases, including spatial biases and clock biases. To compute spatial biases, the host processing system 186 implements a number of methods. FIG. 15 discloses an original bias technique 1500 (Part II.F.2.a.). FIG. 16 discloses a parabolic bias technique 1600 (Part II.F.2.b.). FIG. 17 discloses a base residuals bias technique 1700 (Part II.F.2.c.). FIG. 17A discloses a base correlator bias technique 1700A (Part II.F.2.d.).

Detailed Description Paragraph Right (94):
As shown by an arrow 194, the spatial and clock biases are transmitted to the GPS processing system 700 of the vehicle 102. The GPS processing system 700 uses these biases to eliminate errors in vehicle position estimates.

Detailed Description Paragraph Right (95):
B. GPS Processing System

Detailed Description Paragraph Right (96):
The GPS processing system 700 utilizes vehicle position data from a terrestrial position determination system to derive the first position estimate of the vehicle 102. In the preferred embodiment, the terrestrial position determination system comprises the NAVSTAR GPS, which is currently being developed by the U.S. government, and/or Earth-based pseudolites.

Detailed Description Paragraph Right (97):
AS shown in FIG. 1A, 24 man-made electronic GPS satellites 132-170 in six orbits 174-184 are currently envisioned for the NAVSTAR GPS. They are planned for deployment by 1993. As currently envisioned, the GPS satellites 132-170 will orbit the Earth 172 at an altitude of approximately 14,000 miles and encircle the globe twice a day. Using the C mode of the NAVSTAR GPS, as will be discussed below, it will be possible to determine terrestrial positions within 15 meters in any weather, any time, and most areas of the Earth 172.

Detailed Description Paragraph Right (98):
As of the date of the filing of this document, there are known to be six experimental and seven operational GPS satellites in orbit around the Earth 172. Further, several manufacturers are known to be designing and building GPS receivers, such as the GPS receiver 706 of FIG. 7. As more and more GPS satellites are deployed and operational, the time periods increase when three or more of the experimental GPS satellites are available each day for position tracking.

Detailed Description Paragraph Right (99):
Moreover, the location of the experimental GPS satellites (and all others once deployed) is very predictable. The relative position, or "pseudorange," of these GPS satellites with respect to the GPS receiver 706 on the vehicle 102 can be determined from the electromagnetic signals by two methods.

Detailed Description Paragraph Right (100):
One method is to measure the propagation time delays between transmission and reception of the emanating electromagnetic signals. In the NAVSTAR GPS, the electromagnetic signals are encoded continuously with the time at which the signals are transmitted from the GPS satellites. Needless to say, one can make note of the reception time and subtract the encoded transmission time in order to derive time delays. From the calculated time delays and from knowing the speed at which electromagnetic waves travel through the atmosphere, pseudoranges can be accurately derived. Pseudoranges computed using the foregoing method are referred to in the context of this document as "actual" pseudoranges.

Detailed Description Paragraph Right (101):
Another method involves satellite position data that is encoded in the electromagnetic signals being transmitted from the orbiting GPS satellites. Almanac data relating to the GPS satellite position data of the NAVSTAR GPS is publicly available. Reference to this almanac data in regard to data encoded in the electromagnetic signals allows for an accurate derivation of pseudoranges if the receiver location is known. Pseudoranges computed using the foregoing method are referred to in the context of this document as "estimated" pseudoranges.

Detailed Description Paragraph Right (102):
However, with respect to the previous method of deriving estimated pseudoranges, it should be noted that the satellite position data is updated at the GPS satellite only once an hour on the hour. Consequently, an estimated pseudorange decreases in accuracy over time after each hour until the next hour, when a new estimated pseudorange is computed using updated satellite position data.

Detailed Description Paragraph Right (103):
Reference is again made to FIG. 1A of the drawings wherein the configuration of the fully-operational NAVSTAR GPS is schematically illustrated. Each of the 24 GPS satellites 132-170 transmits electromagnetic signals which can be used to determine the absolute terrestrial position (that is, longitude, latitude, and altitude with respect to the Earth 172's center) of the vehicle 102.

Detailed Description Paragraph Right (104):
Specifically, by knowing the relative position of at least three of the orbiting GPS satellites 132-170, the absolute terrestrial position of the vehicle 102 can be computed via simple geometric theory involving triangulation methods. The accuracy of the terrestrial position estimate depends in part on the number of orbiting GPS satellites 132-170 that are sampled by the vehicle 102. The sampling of more GPS satellites 132-170 in the computation increases the accuracy of the terrestrial position estimate. Conventionally, four GPS satellites, instead of three, are sampled to determine each terrestrial position estimate because of errors contributed by circuit clock differentials among the circuitry of the vehicle 102 and the various GPS satellites 132-170.

Detailed Description Paragraph Right (105):
In the NAVSTAR GPS, electromagnetic signals are continuously transmitted from all of the GPS satellites 132-170 at a single carrier frequency. However, each of the GPS satellites 132-170 has a different modulation scheme, thereby allowing for differentiation of the electromagnetic signals. In the NAVSTAR GPS, the carrier frequency is modulated using a pseudorandom binary code signal (data bit stream) which is unique to each GPS satellite. The pseudorandom binary code signal is used to biphase modulate the carrier frequency. Consequently, the orbiting GPS satellites in the NAVSTAR GPS can be identified when the carrier frequencies are demodulated.

Detailed Description Paragraph Right (106):
Furthermore, the NAVSTAR GPS envisions two modes of modulating the carrier wave using pseudorandom number (PRN) signals. In one mode, referred to as the "coarse/acquisition" (C/A) mode, the PRN signal is a gold code sequence having a chip rate of 1.023 MHz. The gold code sequence is a well-known conventional pseudorandom sequence in the art. A chip is one individual pulse of the pseudorandom code. The chip rate of a pseudorandom code sequence is the rate at which the chips in the sequence are generated. Consequently, the chip rate is equal to the code repetition rate divided by the number of members in the code. Accordingly, with respect to the coarse/acquisition mode of the NAVSTAR GPS, there exists 1,023 chips in each gold code sequence and the sequence is repeated once every millisecond. Use of the 1.023 MHz gold code sequence from four orbiting GPS satellites enables the terrestrial position of the vehicle 102 to be determined to an approximate accuracy of within 60 to 300 meters.

Detailed Description Paragraph Right (107):
The second mode of modulation in the NAVSTAR GPS is commonly referred to as the "precise" or "protected" (P) mode. In the P mode, the pseudorandom code has a chip rate of 10.23 MHz. Moreover, the P mode sequences that are extremely long, so that the sequences repeat no more than once per 276 days. As a result, the terrestrial position of the vehicle 102 can be determined to within an approximate accuracy of 16 to 30 meters.

Detailed Description Paragraph Right (109):
In order for the Earth receivers to differentiate the various C/A signals from the different orbiting GPS satellites, Earth receivers usually include a plurality of different gold code sources for locally generating gold code sequences. Each locally-derived gold code sequence corresponds with each unique gold code sequence from each of the GPS satellites.

Detailed Description Paragraph Right (110):
The locally-derived gold code sequences and the transmitted gold code sequences are cross correlated with each other over gold code sequence intervals of one millisecond. The phase of the locally-derived gold code sequences vary on a chip-by-chip basis, and then within a chip, until the maximum cross correlation function is obtained. Because the cross correlation for two gold code sequences having a length of 1,023 bits is

approximately 16 times as great as the cross correlation function of any of the other combinations of gold code sequences, it is relatively easy to lock the locally derived gold code sequence onto the same gold code sequence that was transmitted by one of the GPS satellites.

Detailed Description Paragraph Right (111):
The gold code sequences from at least four of the GPS satellites in the field of view of an Earth receiver are separated in this manner by using a single channel that is sequentially responsive to each of the locally-derived gold code sequences, or alternatively, by using parallel channels that are simultaneously responsive to the different gold code sequences. After four locally-derived gold code sequences are locked in phase with the gold code sequences received from four GPS satellites in the field of view of the Earth receiver, the relative position of the Earth receiver can be determined to an accuracy of approximately 60 to 300 meters.

Detailed Description Paragraph Right (112):
The foregoing approximate accuracy of the NAVSTAR GPS is affected by (1) the number of GPS satellites transmitting signals to which the Earth receiver is effectively responsive, (2) the variable amplitudes of the received signals, and (3) the magnitude of the cross correlation peaks between the received signals from the different GPS satellites.

Detailed Description Paragraph Right (113):
With reference to FIG. 7, the GPS processing system 700 processes the GPS data from the GPS satellites 132-170 and the pseudolite data from any pseudolite(s) 105. Furthermore, the GPS receiver 706 decodes the C/A signals from the various GPS satellites 132-170.

Detailed Description Paragraph Right (114):
FIGS. 2 and 2A illustrate navigation equations 212 regarding four GPS satellites 200-206 of the NAVSTAR GPS. The four GPS satellites 200, 202, 204, and 206 have respective pseudoranges R0, R2, R4, and R6 and comprise the current constellation of GPS satellites 132-170 recognized by the vehicle 102.

Detailed Description Paragraph Right (115):
The navigation equations 212 include the clock bias C.sub.b between the GPS satellites 200-206 and the vehicle 102. The navigation equations 212 are used to compute the longitude and latitude of the vehicle 102 using the pseudoranges R0, R2, R4, and R6.

Detailed Description Paragraph Right (116):
As is shown in the description block 208, each of the GPS satellites 200, 202, 204, and 206 transmits GPS data that includes timing data (GPS time) and ephemeris data. Using the navigation equations 212, which are well-known in the conventional art and the foregoing timing data, the pseudoranges R0, R2, R4, and R6 can be estimated (called actual pseudoranges) by the GPS processing system 700. Furthermore, using the foregoing ephemeris data and almanac data on the Earth 172, the pseudoranges R0, R2, R4, and R6 can be estimated (called estimated pseudoranges) by the GPS processing system.

Detailed Description Paragraph Right (117):
Turning now to FIG. 6, a representative GPS constellation is shown in operation. Four GPS satellites 200, 202, 204 and 206 are transmitting GPS data. Both the vehicle 102 and the base station 188 are receiving these signals from each of these GPS satellites 200, 202, 204, and 206 on their respective GPS antennas 312 and 316. In the preferred embodiment, both the C/A code and the carrier frequency are received at GPS antennas 312 and 316 for processing.

Detailed Description Paragraph Right (118):
In addition to the four GPS satellites shown in the FIG. 6 is the pseudolite 105. The pseudolite(s) 105 can be strategically placed around the perimeter of any mine pit and can emulate the GPS satellites 200, 202, 204, and 206 as shown in FIG. 6. This arrangement can be extremely useful in situations such as a mine pit, cavity, or the like, in which mining vehicles may be out of view of one or more of the GPS satellites 200, 202, 204, and 206, because of topographic features such as high mine pit walls. The ground-based pseudolite(s) 105 provides additional ranging signals and can thus

improve availability and accuracy of the positioning capability in the present invention.

Detailed Description Paragraph Right (119):
The pseudolite(s) 105 is synchronized with the GPS satellites 200, 202, 204, and 206 and has a signal structure that, while different, is compatible with the GPS satellites 200, 202, 204, and 206. Moreover, the distance (range) between the vehicle 102 and the pseudolite(s) 105 is calculated similarly as the distance between the vehicle 102 and one of GPS satellites 200, 202, 204, and 206. With pseudolite(s) 105, the ranging error does not include selective availability nor ionospheric errors. However, other errors must be accounted for such as tropospheric, pseudolite clock error and multipath errors.

Detailed Description Paragraph Right (120):
In a deep pit surface mining operation, the view of the sky from a vehicle 102 in the mine can be limited by the walls of the mine. Consequently, an adequate number of GPS satellites may not be in view for the GPS processing system 700 to properly derive a first position estimate. In such a case in the present invention, one or more pseudolites 105 can serve as secondary sources. The pseudolite(s) can be placed on the rim of the mine or elsewhere. The pseudolite(s) 105 can be used by the vehicle 102 in conjunction with any visible GPS satellites to obtain accurate first position estimates.

Detailed Description Paragraph Right (121):
It is also envisioned that other forms of secondary sources could be implemented to aid GPS satellites or to completely eliminate the need to receive GPS data from the GPS satellites. Moreover, a laser scanning technique may utilized to give localized ranging data to the vehicle 102 from a secondary reference source.

Detailed Description Paragraph Right (122):
Communication channel 618 represents the communications link between the base station 188 and the vehicle 102. In the preferred embodiment, the communication channel 618 comprises an electromagnetic link established by data-radios 620 and 622 which are transceivers. The communication channel 618 is used to transfer data between the base station 188 and the vehicle 102. It is envisioned that other forms of communication media may be utilized. For example, a laser scanning technique may utilized to convey information from the base station 108 to the vehicle 102.

Detailed Description Paragraph Right (123):
The data radios 620 and 622 are located at the base station 188 and vehicle 102 respectively. The radios 620 and 622 are responsible for exchanging data between the base station 188 and the vehicle 102. The type of data exchanged will be discussed further below.

Detailed Description Paragraph Right (125):
Turning now to FIG. 7, the preferred embodiment of a GPS processing system 700 is shown. The GPS processing system 700 on the vehicle 102 includes a GPS antenna 702. In the preferred embodiment, the GPS antenna 702 is receptive to the radio spectrum of electromagnetic radiation. However, the present invention contemplates reception of any signal by which GPS satellites 132-170 might encode data. In the preferred embodiment, the GPS antenna 702 is the commercially available antenna having Model No. CA3224 from Chu Associates Inc. of Littleton, Mass.

Detailed Description Paragraph Right (126):
The GPS antenna 702 is coupled to a preamplifier 704 so that the signals received at the GPS antenna 702 can be transmitted to the preamplifier 704. The term "couple" in the context of this document means any system and method for establishing communication. Coupling systems and methods may include, for example, electronics, optics, and/or sound techniques as well as any others not expressly described herein. In the preferred embodiment, coupling is commonly electronic and adheres to any one of numerous industry standard electronic interfaces.

Detailed Description Paragraph Right (127):
The preamplifier 704 amplifies and down converts the GPS data received from the GPS antenna 702 so that the GPS data can be processed, or decoded. The present invention

contemplates any method by which the received signals can be amplified. In the preferred embodiment, the preamplifier 704 is the commercially available preamplifier having Model No. 5300, Series GPS RF/IF from Stanford Telecommunications Inc. (STel) of Santa Clara, Calif. The preamplifier 704 is coupled to a GPS receiver 706. The GPS receiver 706 processes the GPS data sent from the GPS satellites 200, 202, 204, and 206 in view of the GPS antenna 702. The GPS receiver 706 computes actual pseudoranges for each of the GPS satellites 200, 202, 204, and 206. Actual pseudoranges are defined in this document as an estimate of the pseudoranges R0, R2, R4, and R6 which is derived from the time delay between the transmission of electromagnetic signals from the GPS satellites and the reception of the electromagnetic signals by the GPS processing system 700. Moreover, in the preferred embodiment, the GPS receiver 706 can process in parallel all of the actual pseudoranges for the GPS satellites 200, 202, 204, and 206.

Detailed Description Paragraph Right (128):
In the preferred embodiment of the present invention, the GPS receiver 706 produces this data when four or more GPS satellites are visible. Using the differential correction techniques described in Part II.F.2. of this document, the GPS processing system 700 can compute (at GPS processor 710) the first position estimate with an accuracy of approximately 25 meters when an optimal constellation of four GPS satellites 200, 202, 204, and 206 is in view. When an optimal constellation of five GPS satellites (not shown) is in view, the GPS processing system 700 of the preferred embodiment can compute the first position estimate with an accuracy of approximately 15 meters. An "optimal" constellation is one in which the relative positions of the GPS satellites in space affords superior triangulation capability, triangulation technology being well known in the art.

Detailed Description Paragraph Right (129):
In the preferred embodiment, the GPS receiver 706 outputs actual pseudoranges and the number of GPS satellites 132-170 currently being sampled. In cases in which the number of GPS satellites 132-170 viewed for a series of first position estimates is less than four, the VPS weighted combiner 1204 (see FIG. 12 and discussion) in the preferred embodiment does not use the first position estimates received from the GPS processing system 700 (specifically, the GPS processor 710) in the computation of the third position estimate.

Detailed Description Paragraph Right (130):
In the preferred embodiment, the GPS receiver 706 comprises a Model Number 5305-NSI receiver, which is commercially available from Stanford Telecommunications Inc. However, any receiver which is capable of providing actual pseudoranges and the number of sampled GPS satellites may be utilized.

Detailed Description Paragraph Right (131):
Because of the type of receiver used in the preferred embodiment, the GPS receiver 706 is coupled to a GPS intercommunication processor 708. In the preferred embodiment, the intercommunication processor 708 is the commercially available 68000 microprocessor from Motorola Inc., of Schaumburg, Illinois, U.S.A. Any processor alone or in combination with the GPS receiver 706 for accomplishing the same purpose as described below may be utilized.

Detailed Description Paragraph Right (132):
The GPS intercommunication processor 708 is further coupled to a GPS processor 710 and a GPS Console 1 712. The GPS intercommunication processor 708 coordinates data exchange between these three devices. Specifically, the GPS intercommunication processor 708 receives pseudorange data from the GPS receiver 706 which it passes on to the GPS processor 710. The pseudorange data includes, for example, the actual pseudoranges computed by the GPS receiver 706, the number of GPS satellites 200, 202, 204, and 206 currently being viewed by the GPS receiver 706, and other GPS data needed by the GPS processor 710 to compute the estimated pseudoranges for each of the GPS satellites 200, 202, 204, and 206. The GPS intercommunication processor 708 also relays status information regarding the GPS receiver 706 and the GPS processor 710 to the GPS Console 1 712.

Detailed Description Paragraph Right (133):
The GPS intercommunication processor 708 transmits the above information to the GPS

processor 710. In the preferred embodiment, the GPS processor 710 comprises the 68020 microprocessor, which is commercially available from Motorola Inc. FIG. 8 is a low level flow diagram 800 illustrating the functioning of the software in the GPS processor 710.

Detailed Description Paragraph Right (134):
The GPS processor 710 uses a number of algorithms and methods to process the data it receives including, for example, a GPS Kalman filter 802, which is shown in FIG. 8. The Kalman filter 802 is well known in the conventional art. In the preferred embodiment, the GPS Kalman filter 802 is a module in the software of the GPS processor 710.

Detailed Description Paragraph Right (135):
In part, the function of the Kalman filter 802 is to filter out noise associated with the pseudorange data. The noise may include, for example, ionospheric, clock, and/or receiver noise. The GPS Kalman filter 802 of the host processing system 186 at the base station 188 computes spatial and clock biases which are both transmitted to the vehicle 102 for increasing the accuracy of first position estimates (as discussed in Part II.F.2. of this document). In contrast, the GPS Kalman filter 802 in the vehicle 102 takes into consideration the spatial and clock biases which are received from the base station 188.

Detailed Description Paragraph Right (136):
The GPS Kalman filter 802 functions in a semi-adaptive manner. In other words, the GPS Kalman filter 802 automatically modifies its threshold of acceptable data perturbations, depending on the velocity of the vehicle 102. The term "perturbation" in the context of this document refers to a deviation from a regular course. The semi-adaptive functioning of the GPS Kalman filter 802 optimizes the response and the accuracy of the present invention.

Detailed Description Paragraph Right (137):
Generally, when the vehicle 102 increases its velocity by a specified amount, the GPS Kalman filter 802 will raise its acceptable noise threshold. Similarly, when the vehicle 102 decreases its velocity by a specified amount the GPS Kalman filter 802 will lower its acceptable noise threshold. This automatic optimization technique of the present invention provides the highest degree of accuracy under both moving and stationery conditions.

Detailed Description Paragraph Right (138):
In the best mode of the present invention, the threshold of the GPS Kalman filter 802 does not vary continuously or in very minute discreet intervals. Rather, the intervals are larger discreet intervals and, therefore, less accurate than a continuously varying filter. However, the Kalman filter 802 of the present invention is easy to implement, less costly, and requires less computation time than with a continuously varying filter. However, it should be noted that using a continuously varying filter is possible and is intended to be included herein.

Detailed Description Paragraph Right (139):
For operation, the GPS Kalman filter 802 must be given an initial value at system start-up. From the initial value and GPS data collected by the GPS receiver 706, the GPS Kalman filter 802 extrapolates a current state (which includes the first position estimate and the vehicle velocity for northing, easting and altitude). The GPS Kalman filter 802 operates in a cyclical manner. In other words, the extrapolated current state is assumed to be the initial value for the next iteration. It is combined/filtered with new GPS data (an update) to derive a new current state.

Detailed Description Paragraph Right (140):
The way that the GPS data is utilized is dependent on a priori saved file called a control file 820. The control file 820 will determine the following: (1) the noise threshold, (2) the speed of response, (3) the initial states of vehicle position and velocity, (4) the extent of deviation before a reset of the GPS Kalman filter 802 occurs, (5) the number of bad measurements allowed, and/or (6) the time allotted between measurements.

Detailed Description Paragraph Right (141):

The GPS processor 710 then computes the estimated pseudoranges, the first position estimate, and the vehicle velocity (from Doppler shift) using the above current state and any biases, including the clock biases and the spatial biases. However, the GPS processor 710 discards the computed velocity data when the C/A code, rather than the carrier frequency, is utilized by the GPS receiver 706 to derive the vehicle velocity. The rationale for discarding the vehicle velocity is that experimentation has shown that it is not adequately accurate when derived from the C/A code.

Detailed Description Paragraph Right (142):
Vehicle velocities derived from the carrier frequency (Doppler shift) are much more accurate than the velocities derived from the C/A code. In the preferred embodiment, the first estimated position (and vehicle velocity if derived from the carrier frequency) are encoded on GPS Signal 716 and sent on to the VPS main processor 1002 shown on FIG. 10.

Detailed Description Paragraph Right (143):
As previously discussed, the GPS processor 710 analyzes both the carrier frequency and the C/A code. Unlike data demodulated from the C/A code, data may be retrieved from the carrier frequency by the GPS receiver 706 at approximately 50 Hz (not approximately 2 Hz, as is the case for demodulating C/A code). This increased speed allows the present invention to produce more precise position and velocity determinations with less error.

Detailed Description Paragraph Right (144):
FIG. 8 illustrates other functions of the GPS processor 710 in the preferred embodiment. However, the present invention contemplates any method by which GPS data can be processed to determine pseudoranges. As shown at a flowchart block 816, a console function controls the operation of the GPS console 2. This console function regulates the operation of the GPS Kalman filter 802 by providing a user interface into the filter.

Detailed Description Paragraph Right (145):
The VPS communications function 818 controls the outputs of the GPS Kalman filter 802 which are directed to the VPS 1000. At a flowchart block 806, it is shown that the GPS Kalman filter 802 requests and decodes data from the GPS receiver 706, which data is routed through an IPROTO function 804 shown at a flowchart block 804.

Detailed Description Paragraph Right (146):
As shown, the IPROTO function 804 resides in the GPS intercommunications processor 708 and executes tasks associated with the GPS intercommunications processor 708. In the preferred embodiment, the IPROTO function 804 is the model number XVME-081, which is commercially available from Xycom Inc.

Detailed Description Paragraph Right (147):
As shown at a flowchart block 810 the data transmitted over the communication channel 618 enters the IPROTO function 804. Much of this data is ultimately destined for the GPS Kalman filter 802. The communications manager function shown at a flowchart block 808, coordinates the incoming data from the IPROTO function. The communications manager function 808 also coordinates data received from an ICC function which is shown in a flowchart block 812. The ICC function 812 exchanges data with the data-radio 714 (via GPS intercommunications processors 720) and the GPS data collection device 718 as shown.

Detailed Description Paragraph Right (148):
The GPS console 712 is well known in the art. Many types of devices are commercially available which provide the desired function. One such device is commercially available from Digital Equipment Corporation of Maynard, Mass. Model Number VT220. The GPS console 712 displays processor activity data regarding the GPS intercommunications processor 708 and the GPS processor 710.

Detailed Description Paragraph Right (149):
The GPS processor 710 is coupled to a GPS console 722 and a GPS communications interface processor 720. The GPS console 722 is well known in the art. Many types of devices are commercially available which provide the desired console function. One such device is commercially available from Digital Equipment Corporation of Maynard,

Mass. Model Number VT220. The GPS console 722 provides the user interface from which the GPS processor 710 can be activated and monitored.

Detailed Description Paragraph Right (150):
The GPS communications interface processor 720 is essentially an I/O board. It is coupled to a data-radio 714 and a GPS data collection device 718. The GPS communications interface processor 720 coordinates data exchange between the GPS processor 710 and both the data-radio 714 and the GPS data collection device 718. The communications interface processor 720 in the preferred embodiment is the model no. MVME331, which is commercially available from Motorola Inc., U.S.A.

Detailed Description Paragraph Right (151):
The data-radio 714 establishes a communication link between the GPS processor 710 (through the GPS communications interface processor 720) at the vehicle 102 to a similar data-radio 714 located at the base station 188 (see FIG. 6). In the preferred embodiment, the data-radio 714 communicates synchronously at 9600 baud using RF frequencies. The data-radio 714 at the base station 188 provides periodic updates on the amount of spatial bias and clock bias for each satellite to the data-radio 714 at the vehicle 102 at a rate of 2 Hz (twice per second). Spatial and clock biases computed by the base station 188 will be discussed further below.

Detailed Description Paragraph Right (152):
The GPS data collection device 718 can be any of numerous common electronic processing and storage devices such as a desktop computer. Any personal computer (PC) manufactured by the International Business Machines Corporation (IBM) of Boca Raton, Fla., U.S.A., can be implemented.

Detailed Description Paragraph Right (154):
The MPS 900 of the preferred embodiment is illustrated in FIG. 9. The MPS 900 derives the second position estimate of the vehicle 102. Usually, this second position estimate is combined and filtered with the first position estimate to thereby derive a more accurate third position estimate. However, it is envisioned that in some instances the second position estimate may be utilized exclusively as the third position estimate, when the first position estimate is deemed to be drastically inaccurate.

Detailed Description Paragraph Right (156):
The IRU 904 comprises ring-laser gyroscopes and accelerometers of known design. The IRU 904 used in the preferred embodiment is a replica of the system used by Boeing 767 aircrafts to determine aircraft position, except that the IRU 904 has been modified to account for the lesser dynamics (for example, velocity) that the vehicle 102 exhibits relative to that of a 767 aircraft.

Detailed Description Paragraph Right (157):
The IRU 904 can output vehicle position at 5 Hz, velocity at 10 Hz, roll at 50 Hz, pitch at 50 Hz, and yaw data at 50 Hz. Furthermore, in the preferred embodiment, the vehicle odometer 902 can output the distance traveled by the vehicle 102 at 20 Hz.

Detailed Description Paragraph Right (158):
The laser gyroscopes of the IRU 904, in order to function properly, must at first be given an estimate of the vehicle 102's latitude, longitude and altitude. Using this data as a baseline position estimate, the gyroscopes then use a predefined calibration in conjunction with forces associated with the rotation of the Earth 172 to determine an estimate of the vehicle 102's current position.

Detailed Description Paragraph Right (159):
This information is then combined by the IRU 904 with data acquired by the IRU 904 accelerometers to produce a more accurate, second position estimate of the vehicle's current position. The second position estimate from the IRU 904 and the data from the vehicle odometer 902 are transmitted to the MPS intercommunications processor 906 as shown by respective arrows 910 and 908 of FIG. 9. Arrow 114 of FIG. 1 includes arrows 908 and 910.

Detailed Description Paragraph Right (160):
Upon experimentation, it has been determined that the IRU 904 may provide erroneous

second position estimates of the vehicle 102 due to imprecise constituent parts. More specifically, in the preferred embodiment, it has been observed that the directional output of the IRU 904 has drifted counterclockwise from the direction north during operation. The drift is dependent upon the direction in which the vehicle 102, and consequently the IRU 904, is travelling.

Detailed Description Paragraph Right (163):
Turning now to FIG. 10, the preferred embodiment of the architecture of the VPS 1000 is depicted. FIG. 11 shows in detail a diagram of the VPS 1000 connected to the GPS processing system 700 and MPS 900.

Detailed Description Paragraph Right (164):
GPS processing system 700 and MPS 900 are independently coupled to the VPS main processor 1002. The independent coupling is an important novel feature of the present invention. Because they are independent, the failure of one of the systems will not cause the other to become inoperative. Thus, if the GPS processing system 700 is not operative, data can still be collected and processed by the MPS 900 and, consequently, the VPS 1000. The GPS processing system 700 and the MPS 900 transmit signals 716, 908, 910 to the VPS main processor 1002, as shown. These signals contain position, velocity, time, pitch, roll, yaw, and distance data (see FIGS. 7 and 9 and associated discussions).

Detailed Description Paragraph Right (165):
The VPS main processor 1002 is coupled to the VPS I/O processor 1004. The VPS main processor 1002 transmits a signal 1008 to a VPS I/O processor 1004, as shown. The signal 1008 comprises the third position estimate. The third position estimate is derived from the GPS, IRU, and odometer data noted above, and more specifically, the first and second position estimates of the vehicle 102.

Detailed Description Paragraph Right (166):
The present invention contemplates any system and method by which the signals indicated by arrows 716, 908 and 910 can be received by the VPS main processor 1002 from the GPS processing system 700 and MPS system 900 and forwarded to the VPS main processor 1002. The VPS main processor 1002 is the 68020 microprocessor, which is commercially available from Motorola Inc., U.S.A.

Detailed Description Paragraph Right (167):
FIG. 12 is an intermediate level block diagram 1200 of a VPS main processor 1002 of FIG. 10 showing a VPS Kalman filter 1202 and a weighted combiner 1200. As shown, the GPS signal 716 and the odometer signal 908 are transmitted directly to a weighted combiner 1204. The IRU signal 910 is transmitted into a VPS Kalman filter 1202. In the preferred embodiment, the GPS signal 716 is transmitted at a rate of 2 Hz. The odometer signal 908 is transmitted at a rate of 20 Hz. Moreover, the IRU signal 910, which includes the second position estimate, is transmitted at a rate of 50 Hz.

Detailed Description Paragraph Right (169):
The weighted combiner 1204 processes the signals and gives a predetermined weighing factor to each data based on the estimated accuracy of data gathering technique used. Thus, in the preferred embodiment, the first position estimate of the GPS signal 716 is weighted heavier than the second position estimate of the IRU signal 910. The reason for this weighing scheme is that the first position estimate is inherently more accurate than the second position estimate from the IRU 904.

Detailed Description Paragraph Right (170):
However, velocity can be more accurately determined by the IRU. Therefore, the velocity component of the IRU signal 910 can be weighted heavier than the velocity component of the GPS signal 16. In the preferred embodiment of the present invention, the velocity component of the IRU signal 10 is used exclusive of the velocity component of the GPS signal 716.

Detailed Description Paragraph Right (171):
The weighted combiner 1204 produces an output 1206 at 20 Hz. The output 1206 contains all computed data and is sent to two locations: the VPS Kalman filter 1202, as shown by an arrow 1208 and the VPS I/O processor 1004, as shown by an arrow 1008. The output 1206 contains time information relative to the GPS satellites. The output 1206 further

contains information relative to vehicle position, velocity, yaw, pitch, and roll. Finally, note that the VPS output 1206 comprises the third position estimate of the vehicle 102.

Detailed Description Paragraph Right (172):
Another output shown at an arrow 1018 from the weighted combiner 1204 contains only velocity data pertaining to the vehicle 102. Velocity data is sent to the GPS processing system 700 from the VPS main processor 1002. The velocity data is used to increase the accuracy of first position estimates as is discussed hereinafter.

Detailed Description Paragraph Right (174):
FIG. 12A illustrates a super Kalman filter 1200A of the present invention. The super Kalman filter 1200A is a system and method for processing data to increase the accuracy of position estimates of the vehicle 102. Specifically, the super Kalman filter directly increases the accuracy of the first position estimate. Accordingly, the accuracy of the third position estimate is indirectly enhanced. In the preferred embodiment, the super Kalman filter 1200A comprises software within the architectures of the GPS processing system 700 at FIG. 7 and the VPS 1000 at FIG. 10. It is envisioned that the super Kalman filter 1200A could be constructed in hardware, for example, as in an integrated circuit, an optical filter, or the like.

Detailed Description Paragraph Right (175):
As shown by the arrow an 1210, the GPS Kalman filter 802 receives first data from a terrestrial position determination system, which could include, for example, GPS data and/or pseudolite data. The GPS Kalman filter 802 operates on the data and outputs the first position estimate (FPE), as indicated by the arrow 716.

Detailed Description Paragraph Right (177):
The weighted combiner 1204 receives the FPE and the SPE as indicated by respective arrows 716 and 1210. The weighted combiner 1204 outputs the velocity 1018 of the vehicle 102 to the GPS Kalman filter 802. The GPS Kalman filter 802 adapts pursuant to the vehicle velocity 1018 of the vehicle to increase the accuracy of the FPE at arrow 716.

Detailed Description Paragraph Right (178):
The GPS Kalman filter 802 can be designed to adapt in discreet time intervals or to adapt continuously. In the preferred embodiment, the GPS Kalman filter 802 adapts in discreet time intervals due to a balance between cost and performance.

Detailed Description Paragraph Right (179):
It is envisioned that only one Kalman filter (not shown) could be implemented to provide for an accurate terrestrial position determination system. More specifically, it is possible to have the GPS processing system 700 and the MPS 900 (having an odometer 902 and/or an IRU 904) connected to only one Kalman filter which derives the third position estimate. However, such a configuration would not possess all of the favorable attributes as the preferred embodiment.

Detailed Description Paragraph Right (180):
The super Kalman filter of FIG. 12 and 12A has the beneficial attributes of both a single Kalman filter and of separate Kalman filters. As configured, the GPS Kalman filter 710 and the VPS Kalman filter 1202 can continuously exchange data to thereby increase the accuracy of first and second position estimates. Consequently, third position estimates are enhanced. In a sense, a single Kalman filtering system resides between the ultimate output of the third position estimate and the position data being inputted.

Detailed Description Paragraph Right (181):
In a different sense, the GPS Kalman filter 710 and the VPS Kalman filter 1202 act entirely as separate, independent filters. If, for example, either GPS data or MPS data is tainted, then the tainted data can be totally or partially disregarded via the weighted combiner 1204 without affecting the accuracy of the non-tainted data. In a system utilizing a single Kalman filter, the ultimate output, or third position estimate, will be substantially inaccurate if either the GPS data or the MPS data is substantially tainted.

Detailed Description Paragraph Right (183):
In the preferred embodiment, the VPS communications interface processor 1020 is coupled to three different devices: (1) a VPS console 1012, (2) a data collection device 1014, and (3) the navigation system 1022. The VPS communications interface processor 1020 routes the data, including the third position estimate, contained in output 1016 to the above three devices at a rate of 20 Hz.

Detailed Description Paragraph Right (186):
The navigation system 1022 comprises the features associated with the navigation of the vehicle 102. The VPS 1000 transmits the third position estimate to the navigation system 1022, so that the navigation system 1022 can accurately and safely guide the autonomous vehicle 102.

Detailed Description Paragraph Right (187):
With reference to FIG. 7, the host processing system 186 at the base station 188 comprises the GPS processing system 700 of FIG. 7. The purposes of the host processing system 186 at the base station 188 are to (1) monitor the operation of the vehicle 102, (2) provide a known terrestrial reference point from which spatial biases (see differential bias techniques, Part II.F.2.) can be produced, and (3) provide any other information to the vehicle 102 when necessary over the high-speed data communication channel 618.

Detailed Description Paragraph Right (188):
In the preferred embodiment, the base station 188 will be located close to the vehicle 102, preferably within 20 miles. The close geographical relationship will provide for effective radio communication between the base station 188 and the vehicle 102 over the communication channel 618. It will also provide an accurate reference point for comparing satellite transmissions received by the vehicle 102 with those received by the base station 188.

Detailed Description Paragraph Right (189):
A geographically proximate reference point is needed in order to compute accurate spatial biases. Spatial and clock biases are, in effect, the common mode noise that exists inherently in the NAVSTAR GPS and the GPS processing system 700. Once computed at the base station 188, the spatial and clock biases are then sent to the vehicle 102 using the data-radio 714, as shown in FIG. 7. The spatial biases are computed using various methods which are discussed further below.

Detailed Description Paragraph Right (190):
In the preferred embodiment of the present invention, the host processing system 186 at the base station 188 further coordinates the autonomous activities of the vehicle 102 and interfaces the VPS 1000 with human supervisors.

Detailed Description Paragraph Right (191):
The present invention improves the accuracy of the position estimates of the vehicle 102 via a number of differential correction techniques. These differential bias techniques are used to enhance the first, second, and third position estimates.

Detailed Description Paragraph Right (192):
Several of these differential correction techniques are designed to directly remove errors (noise or interference) in the calculation of pseudoranges R0, R2, R4, and R6 (both actual and estimated pseudoranges). The removal of these errors results in a more precise first position estimate, which is outputted by the GPS processing system 700 to the VPS 1000, and ultimately, in a more precise third position estimate, which is outputted by the VPS 1000 to the navigation system 1022.

Detailed Description Paragraph Right (193):
In the preferred embodiment, the host processing system 186 at the base station 188 is responsible for executing these differential techniques and for forwarding the results to the vehicle 102. Recall that the host processing system 186 comprises the GPS processing system 700, just as the vehicle 102. The term "differential" is used because the base station 188 and the vehicle 102 use independent but virtually an identical GPS processing system 700. Furthermore, because the base station 188 is stationary and its absolute position is known, it serves as a reference point from which to measure electronic errors (noise or interference) and other phenomena

inducing errors.

Detailed Description Paragraph Right (194):
FIG. 13 is a flowchart 1300 of the constellation effects method for improving the accuracy of first position estimates in the preferred embodiment of the present invention. The method may be implemented in the GPS processing system 700 at the vehicle 102. Alternatively, the method may be implemented in the host processing system 186 at the base station 188. In the latter case, the information determined by the method would subsequently be communicated to the vehicle 102 for appropriate enhancement of first position estimates.

Detailed Description Paragraph Right (195):
The flowchart 1300 shows a method for selecting the best satellite constellation in view of the GPS antenna 702. For the vehicle 102, many of the GPS satellites 132-170 may be in view of the GPS antenna 702. Only a subset of these satellites are selected to form a particular constellation of any number of satellites (at least four in the preferred embodiment).

Detailed Description Paragraph Right (196):
Essentially, the "best" or "optimal" constellation is selected based upon geometrical considerations. The location in space of the GPS satellites 132-170 in view of the GPS antenna and the intended path of the vehicle 102 are taken into account as will be discussed in detail below.

Detailed Description Paragraph Right (197):
The flowchart 1300 begins at a flowchart block 1302. At flowchart 1304, the estimated pseudoranges of each GPS satellite in view of and relative to the GPS antenna 702 are computed. Estimated pseudoranges are defined in the context of this document as estimated pseudoranges derived from almanac data and the ephemeris from GPS satellites. Almanac data refers to previously recorded data which stores the location in space of the GPS satellites 132-170 at specific times during the day.

Detailed Description Paragraph Right (198):
For the NAVSTAR GPS, the almanac data is in the form of an equations with variables. These almanac equations are publicly available from the U.S. government. Some of the variables identify the GPS satellites 132-170. Further requisite inputs include the time at which an estimated pseudorange is to be determined and the known location of the relevant point on the Earth.

Detailed Description Paragraph Right (199):
To determine the estimated pseudoranges pertaining to each GPS satellite, the following information is inserted into these almanac equations: (1) the parameters identifying the GPS satellites, which are encoded in the GPS data from the GPS satellites, (2) the current time, and (3) the known location of the base station 188.

Detailed Description Paragraph Right (200):
Next, at flowchart block 1306, the estimated pseudoranges are plotted using polar coordinates. FIG. 14 is a polar plot 1400 on a coordinate system 1402 illustrating a set of estimated pseudoranges circles 1404, 1406, 1408, and 1410 pertaining to a GPS satellite constellation of four GPS satellites (not shown). The estimated pseudorange circles 1404, 1406, 1408, and 1410 are drawn so that an intersection exists at the center 1412 of the polar map 1400. The coordinate system 1402 reflects azimuth from the direction north as indicated.

Detailed Description Paragraph Right (201):
The relative distances between the GPS satellites and the GPS antenna are also represented in the polar map 1400 by the size of the estimated pseudorange circles 1404, 1406, 1408, and 1410. Specifically, for example, the GPS satellite represented by the estimated pseudorange circle 1406 is further away than the GPS satellite represented by the estimated pseudorange circle 1408.

Detailed Description Paragraph Right (202):
With reference to FIG. 14, a shaded ellipsoid region 1412 shows the possible position of the vehicle 102 when the GPS satellites (not shown) giving rise to the estimated pseudorange circles 1406 and 1408 are considered. An important parameter in the

ellipsoid representation is the ratio between the semi-major and semi-minor access of the ellipsoid, called the geometric ratio of access factor (GRAF). It is envisioned that the GRAF can be computed at a next flowchart block 1308.

Detailed Description Paragraph Right (203):
With reference to the flowchart block 1308, the GRAF is used along with the angle of the major access to compute a weighing factor, which will ultimately assist the GPS processing system 700 to compute a more accurate first position estimate as described below.

Detailed Description Paragraph Right (204):
As shown in flowchart block 1312, the GPS Kalman filter 802 in the GPS processing system 700 at the vehicle 102 is modified to accommodate for the shape of the estimated ellipsoid and for the computed northing-easting coordinates of the vehicle 102, as illustrated in FIG. 14. Moreover, as indicated by an arrow 1314, the foregoing procedure is repeated continuously so as to continuously enhance the estimated position of the center 1412. At a flowchart block 1316, the optimal satellite constellation for the desired vehicle path is determined. The optimal constellation will be one that gives the least error perpendicular to the desired vehicle path.

Detailed Description Paragraph Right (205):
As shown at a flowchart block 1318, the optimal satellite constellation is transmitted to the vehicle 102 over the data radio 714. The vehicle 102 uses the optimal satellite constellation to compute first position estimates.

Detailed Description Paragraph Right (207):
The original bias technique may be implemented in the GPS processing system 700 at the vehicle 102. Furthermore, the original bias technique may be implemented in the host processing system 186 at the base station 188. In the latter approach, the information determined by the method would subsequently be communicated to the vehicle 102 for appropriate enhancement of first position estimates. Furthermore, the preferred embodiment adopts the latter approach and implements the original bias technique in the host processing system 186 at the base station 188.

Detailed Description Paragraph Right (208):
The original bias technique as shown in FIG. 15 begins at flowchart block 1502. As shown at a flowchart block 1504, the actual pseudorange (base actual pseudorange) and the estimated pseudorange (base estimate pseudorange) for each GPS satellite in view of the GPS antenna 702 are computed in the host processing system 186 at the base station 188. The base actual pseudorange is computed independently of the base estimated pseudorange. The base actual pseudorange is computed by the GPS receiver 706 in the host processing system 186. Moreover, the base estimated pseudorange is computed by the GPS processor 710.

Detailed Description Paragraph Right (209):
Base actual pseudoranges are calculated by measuring the propagation time lapse between transmission of electromagnetic signals from a GPS satellite (or pseudolite) and reception of the signals at the host processing system 186 at the base station 188. The electromagnetic signals encode the time of transmission. Further, the GPS receiver 706 records the time of reception. By assuming that these electromagnetic signals travel at the speed of light, or 2.9979245898 * 108 meters per second, the actual pseudorange for each satellite can be determined by multiplying the propagation time lapse by the speed of light (in the appropriate units).

Detailed Description Paragraph Right (210):
Base estimated pseudoranges are computed from (1) almanac data (in NAVSTAR GPS, an almanac equation), (2) the time of transmission of the electromagnetic signals from the GPS satellites, and (3) the known position (base known position) of the base station 188. The transmission time and the base known position (BKP) is inserted into the almanac equation to derive an estimated pseudorange for a satellite.

Detailed Description Paragraph Right (211):
Clock biases (base clock bias) between the circuitry clocks of the host processing system 186 and the recognized GPS satellites are also computed, as shown at the flowchart block 1604. In the preferred embodiment, one base clock bias is calculated

for all of the satellites. The base clock bias is computed by counting clock pulses of a satellite and the host processing system 188 over a preselected time period. The pulses are then compared to derive a difference. The difference is then multiplied by the speed of light, or 2.998 * 108 meters per second, so as to convert the clock bias into units of length. However, it should be noted that any method of computing and expressing a base clock bias can be incorporated into the present invention.

Detailed Description Paragraph Right (212):
As shown in flowchart block 1508, a spatial bias (original bias) is calculated by subtracting both the base estimated pseudorange and the base clock bias (in units of length) from base actual pseudorange. The original bias is caused by many different effects, such as atmospheric conditions, receiver error, etc. It should be noted that the calculation of the original bias cannot be performed by using the vehicle 102 as a reference point, because the actual position of the vehicle 102 is not known. However, the computation of the original biases could be performed at the vehicle 102.

Detailed Description Paragraph Right (213):
As shown at a flowchart block 1510, the GPS Kalman filter 802 in the host processing system 188 is updated with the original bias. Further, as shown by an arrow 1512, the process of computing original biases is performed continuously and the derived original biases are used to iteratively update the GPS Kalman filter 802.

Detailed Description Paragraph Right (214):
Because the vehicle 102 is in close proximity to the base station 188, the error in the pseudorange computations is assumed to be identical. Therefore, the original bias which has been determined as shown in the flowchart block 1508 is also used to modify the actual pseudoranges produced by the GPS processing system 700 of the vehicle 102. Accordingly, as shown at a flowchart block 1514, the original biases are transmitted from the base station 188 to the vehicle 102 using the data radios 620 and 622.

Detailed Description Paragraph Right (215):
The original biases are used to update the GPS Kalman filter 802 in the vehicle 102. The updating of the GPS Kalman filter 802 results in more accurate first position estimates.

Detailed Description Paragraph Right (216):
As the GPS satellites 132-170 rise and fall in the sky, the path formed by each GPS satellite 132-170 follows a parabola with respect to tracking pseudoranges on or near the Earth's surface. Therefore, a parabolic function can be derived which represents the path of each GPS satellite in the sky. The foregoing describes the essence of the parabolic bias technique, which is performed in the host processing system 186 at the base station 188 in the preferred embodiment. It should be noted, however, that the parabolic bias technique may be performed at the vehicle 102.

Detailed Description Paragraph Right (217):
Turning now to FIG. 16, a flowchart 1600 illustrates the parabolic bias technique. A parabolic function (model) is computed for each GPS satellite in the view of the GPS antenna 702 at the base station 188.

Detailed Description Paragraph Right (218):
The flowchart 1600 begins at a flowchart block 1602. As shown at a flowchart block 1604, at a time t(n), actual pseudoranges are determined for each GPS satellite in view of the GPS antenna 702 at the base station 188, using the GPS receiver 706, as described above. As shown at a flowchart block 1606, the actual pseudoranges (for each GPS satellite) are incorporated into parabolic best fit models for each GPS satellite. Thus, at the flowchart block 1606 one point is added on the parabolic model for each GPS satellite.

Detailed Description Paragraph Right (219):
As shown at a flowchart block 1608, a test is made as to whether enough points on the parabolic models have been determined to estimate a parabolic function for each GPS satellite. The number of points that have been collected will determine a particular statistical R.sup.2 value. In the preferred embodiment, the R.sup.2 value is computed as follows: ##EQU1##

Detailed Description Paragraph Right (221):
As shown at the flowchart block 1608, if this R.sup.2 value is greater than 0.98 in the preferred embodiment, then the parabolic model is deemed to be accurate enough to estimate the future path of the GPS satellite. If the R.sup.2 value is less than or equal to 0.98, then more points on the parabolic model must be computed. These points are computed by incorporating the pseudorange data which is continually being computed by the GPS receiver 706.

Detailed Description Paragraph Right (222):
As shown at a flowchart block 1610, the N value increments to show that the time at which the pseudorange is computed, as shown in the flowchart block 1604, has increased. Because the GPS receiver 706 outputs actual pseudoranges for each GPS satellite at 2 Hz (twice a second), each N increment should represent approximately one half second.

Detailed Description Paragraph Right (224):
As shown at the flowchart block 1614, for the time T(n+1) the locus point on each of the parabolic models is computed. The locus points are the expected actual pseudoranges of the GPS satellites at time T(n+1). Once this locus point is computed, the range for the locus point (distance between the GPS antenna 702 and the GPS satellite) is computed, as shown at a flowchart block 1616.

Detailed Description Paragraph Right (225):
At a flowchart block 1618, the actual pseudoranges are computed for time T(n+1), which is the current time in the preferred embodiment. The actual pseudoranges are computed by the GPS receiver 706 as described above. These actual pseudoranges at T(n+1) are incorporated into the parabolic best fit models during the next iteration of the flowchart 1600.

Detailed Description Paragraph Right (227):
As indicated in flowchart block 1624, the parabolic biases are then transmitted to the GPS processing system 700 of the vehicle 102 via the data radio 714. The GPS processing system 700 at the vehicle 102 utilizes the parabolic biases to increase the accuracy of its actual pseudorange (vehicle actual pseudoranges) calculations to thereby increase the accuracy of first position estimates.

Detailed Description Paragraph Right (228):
FIG. 17 illustrates a flowchart 1700 for implementing the base residuals bias technique. In the preferred embodiment, the base residuals bias technique is performed in the host processing system 186 at the base station 188. After the base residuals bias has been computed at the base station 188, it is transmitted to the GPS processing system 700 of the vehicle 102. The GPS processing system 700 at the vehicle 102 uses the base residuals bias to enhance the accuracy of first position estimates.

Detailed Description Paragraph Right (229):
A base residual bias in the context of this document is a difference in the base known position of the base station 188 and the position estimate (first position estimate, if calculated by the vehicle 102) of the base station 188 which is computed by the host processing system 186 at the base station 188. To illustrate how this functions, assume the base station 188 is at the corner of Elm and Maple streets. Also assume the GPS processing system 700 at the base station 188 estimates the position of the base station 188 to be four miles due south of the base known position (the corner of Elm and Maple). It is obvious that the base residuals bias is a distance equal to four miles in a due south direction.

Detailed Description Paragraph Right (230):
Because the GPS processing system 700 on the vehicle 102 is identical to the GPS processing system 700 at the base station 188, the four mile error in computation can be deemed to be occurring at the vehicle 102 as well as the base station 188. The vehicle 102 can then use this information in its GPS processor 710. In effect, the GPS processor on the vehicle 102 will modify its first position estimates to account for a four mile due south error in the data.

Detailed Description Paragraph Right (232):
At a flowchart block 1706, base actual pseudoranges, base estimated pseudoranges, and

base clock biases are computed by the host processing system 186 at the base station 188. If the GPS receiver 706 on the vehicle 102 is configured to read data from a particular constellation of GPS satellites (not shown), then the GPS receiver 706 at the base station 188 will use the same satellite constellation.

Detailed Description Paragraph Right (233):
As indicated in flowchart block 1708, a position estimate (base position estimate) of the base station 188 is computed. In the preferred embodiment, the base position estimate is computed in the same way as the first position estimate at the vehicle 102.

Detailed Description Paragraph Right (235):
The base residuals bias is transmitted to the vehicle 102 via the data radio 714, as indicated in flowchart block 1712. The base residuals bias is processed at the GPS processor 710 of the vehicle 102 to enhance the accuracy of the first position estimate.

Detailed Description Paragraph Right (236):
FIG. 17A illustrates a high level flowchart 1700A of a base correlator technique utilized in the present invention to improve the accuracy of the first position estimates of the vehicle 102. Generally, the technique involves using the known position of a reference point as a way of increasing accuracy. In the preferred embodiment, the base station 188 serves as the reference point. The methodology of flowchart 1700A will be discussed in detail below with specific reference to FIG. 6.

Detailed Description Paragraph Right (238):
Specifically, recall that the original bias is calculated by subtracting both estimated pseudoranges (base estimated pseudorange) and base clock biases from actual pseudoranges (base actual pseudoranges). The base estimated pseudoranges are determined from (1) almanac data, (2) the time of transmission of the satellite signals, and (3) the known position (base known position) of the base station 188. The base clock biases are the differences in the clock times between the transmission circuitry of GPS satellites and/or pseudolites and the reception circuitry of the base station 188. The base clock biases are expressed in terms of units of length by multiplying them by the speed of light. The base actual pseudoranges are determined from the propagation time delays between transmission and reception of the electromagnetic signals sent from GPS satellites and/or pseudolites to the base station 188.

Detailed Description Paragraph Right (239):
Moreover, the parabolic bias is computed by constructing parabolic models for the base actual pseudoranges of each observed GPS satellite and extrapolating values from the parabolic models. In the preferred embodiment, the parabolic biases are the base actual pseudoranges minus the value extrapolated from the constructed parabolic models and minus the base clock biases (in units of length).

Detailed Description Paragraph Right (240):
As shown in flowchart block 1709, the base station i88 transmits to the vehicle 102 along communication channel 618 its base actual pseudoranges, base estimated pseudoranges, base spatial biases, base clock biases, and the base known position of the base station 188. Intended to be a very accurate estimate itself, the base known position can be determined by any appropriate means, including but not limited to, the novel systems and methods of the present invention or any other conventional systems and methods. After the vehicle 102 receives the foregoing information from the base station 188, the GPS processor 710 of the vehicle 102 uses this information in the calculation of its own spatial biases (vehicle spatial biases).

Detailed Description Paragraph Right (241):
Before the vehicle 102 performs computations to derive the vehicle spatial biases at flowchart block 1713, its GPS receiver 706 computes its own actual pseudoranges (vehicle actual pseudoranges), its own estimated pseudoranges (vehicle estimated pseudoranges), and its own clock biases (vehicle clock biases). From the vehicle actual pseudoranges, its GPS processor 710 subtracts the vehicle estimated pseudoranges, the vehicle clock biases, and the base spatial biases which were sent from the base station 188 in flowchart block 1709. The result is a more accurate

calculation of the vehicle spatial bias at the vehicle 102.

Detailed Description Paragraph Right (242):
The vehicle spatial bias is then utilized to more accurately modify the first position estimate (FPE) of the vehicle 102, as shown in flowchart block 1717. It should be noted that the FPE is an estimate of the absolute position (with respect to the Earth 172's center) of the vehicle 102.

Detailed Description Paragraph Right (243):
Beginning with a flowchart block 1721, an iterative method is instituted for improving the FPE of the vehicle 102. The method envisions using the base station 314 as a sort of correlator. In the preferred embodiment, the method is implemented by the GPS Kalman filter 802.

Detailed Description Paragraph Right (244):
At the flowchart block 1721, an estimated relative position (HBE) of the base station 188 with respect to the vehicle 102 is determined. The initial state of the FPE is assumed to be the current value of FPE(i), where i is the positive integer value corresponding to the iteration. Consequently, when the method progresses from flowchart block 1717 to block 1721, the current value of FPE(i) will be FPE(0) .

Detailed Description Paragraph Right (245):
Still at flowchart block 1721, the vehicle 102 next calculates an estimated position (base estimated position; BEP) of the base station 188 using the base actual pseudoranges, base estimated pseudoranges, base spatial biases, and base clock biases, which all were transferred to the vehicle 102 from the base station 188. It should be noted that the BEP is an absolute position (relative to the Earth 172's surface). By subtracting the BEP from the FPE, an estimated relative position (HBE) of the base station 188 with respect to the vehicle 102 is determined.

Detailed Description Paragraph Right (246):
As indicated at flowchart block 1725, an HBA is determined. HBA is another estimated relative position of the base station 188 with respect to the vehicle 102. However, unlike the HBE, the HBA is computed by subtracting the base known position (BKP) from the FPE. Thus, HBE and HBA differ in that the former is calculated using GPS data and/or pseudolite data whereas the latter is calculated using the known data.

Detailed Description Paragraph Right (247):
Next at a flowchart block 1729, an offset is computed by subtracting HBE and HBA. In the preferred embodiment, the offset is a vector in a two-dimensional, orthogonal coordinate system. It is envisioned that a three-dimensional vector may be implemented to consider elevational differences between the vehicle 102 and the base station 188.

Detailed Description Paragraph Right (251):
The present invention includes a method by which the future positions of the GPS satellites 132-170 can be predicted with respect to a known absolute position of the base station 188 and/or the vehicle 102. The future positions are based upon estimated pseudoranges calculated by the GPS processor 710 at the host processing system 188 and/or the VPS 1000. Moreover, the computations can be performed at the base station 188 and/or the vehicle 102 and transferred anywhere, if necessary.

Detailed Description Paragraph Right (252):
By predicting the future positions of the GPS satellites 132-170, optimum satellite constellations for the vehicle 102 can be determined well in advance. Thus, the present invention can provide for the prediction of satellite availability and unavailability in a systematic manner. It further allows for future planning related to the operation, service, and maintenance of the vehicle 102.

Detailed Description Paragraph Right (253):
With reference to FIG. 18, a flowchart 1800 illustrates the satellite position predictor method of the present invention. At a flowchart block 1804, for a particular GPS satellite, a future date and time is obtained or selected for any of a number of reasons eluded to above.

Detailed Description Paragraph Right (254):

After a future date and time is acquired, the position of the base station 188 and/or the vehicle 102 is determined, as shown at a flowchart block 1806. In the preferred embodiment, the base station 188 is used as the reference point. The position of the base station 188 could be the base known position or the base position estimate (both discussed in relation to the base residuals technique). In the preferred embodiment, the base known position is utilized and will be referred to hereinafter.

Detailed Description Paragraph Right (255):
As shown at a flowchart block 1808, the almanac data is then consulted. As discussed previously in this document, the almanac data for the NAVSTAR GPS is in the form of almanac equations. By inputting into the almanac equations a satellite's identity, the future date and time, and the base known position, the future position of any satellite can be determined.

Detailed Description Paragraph Right (257):
From the computation of the future positions of satellites, optimal satellite constellations can be determined. Optimal satellite constellations determined using the base station 188 as the reference point can be imputed to the vehicle 102 if close to the base station 188.

Detailed Description Paragraph Right (258):
The weighted path history technique of the present invention improves the accuracy of first position estimates of the vehicle 102 which are derived from the GPS processing system 700. It should be noted that the weighted path history technique could be implemented in an identical fashion as is described below to improve the accuracy of third position estimates derived by the VPS 1000. The weighted path history technique is depicted in FIGS. 19 and 20.

Detailed Description Paragraph Right (259):
Essentially, the weighted path history technique uses previous first position estimates to derive a vehicle path model for testing the validity of future first position estimates. Use of the weighted path history technique results in a reduction to wandering of first position estimates and in enhanced immunities to spurious position computations. The term "wandering" in the context of this document means the tendency of the GPS processing system 700 to estimate erroneous vehicle positions that deviate from the actual path of the vehicle 102.

Detailed Description Paragraph Right (260):
With reference to FIG. 19, the weighted path history flowchart begins at flowchart block 1902. A first position estimate of the vehicle 102 is computed and recorded by the GPS processing system 700, as indicated in a flowchart block 1904. First position estimates are recorded over time. As is shown in FIG. 20, first position estimates 2002, 2004, 2006, 2008, 2010, and 2012 of vehicle 102 are plotted on a diagram 2000 to ultimately derive a vehicle path 2022.

Detailed Description Paragraph Right (261):
At a flowchart block 1906, the first position estimate is used to manipulate/derive a path equation that best fits the path of the vehicle 102. In other words, first position estimates are accumulated over time to derive an accurate "path equation." In the preferred embodiment, the path equation is a second degree (parabolic) equation. However, it should be noted that a third degree equation (having a mathematical inflection) is envisioned for winding vehicle paths and vehicle turns. Furthermore, an embodiment of the present invention could utilize combinations of any types of equations to map an infinite number of different vehicle paths.

Detailed Description Paragraph Right (265):
If less than or equal to 20 first position estimates have been calculated and collected, then the present path equation of flowchart block 1906 is still utilized and will be considered again during the next iteration of flowchart 1900. Moreover, the first position estimate is outputted from the GPS processing system 700, as shown at a flowchart block 1912.

Detailed Description Paragraph Right (266):
Referring back to the flowchart block 1908, if the R.sup.2 value of the path equation is greater than or equal to 0.98, then as shown in a flowchart block 1916, the first

position estimate is modified to be the best fit prediction from the present path equation. Finally, the first position estimate is outputted by the GPS processing system 700, as shown by flowchart block 1912.

Detailed Description Paragraph Right (267):
FIG. 20 illustrates graphically the scenario at issue. The first position estimate 2010 of the vehicle 102 is radically different from the best fit prediction 2006 of the path equation. Therefore, the first position estimate 2010 is replaced by best fit prediction 2006, so long as the R.sup.2 value of the path equation is greater than or equal to preselected threshold and so long as enough position estimates have been sampled.

Detailed Description Paragraph Right (268):
Lines 2014 and 2016 illustrate the scope of acceptability with respect to the first position estimates. These lines 2014 and 2016 represent the physical manifestation of the R.sup.2 value. Thus, the best fit prediction 2006 is outputted from the GPS processing system 700 to the navigation system 1022, instead of the first position estimate 2010 which is outside the span of line 2016.

Detailed Description Paragraph Right (269):
FIG. 20A shows a high level flowchart 2000A of a method for implementing the weighted path history technique as disclosed in FIGS. 19 and 20. The method as shown accommodates for a vehicle travel path having sharp corners, intersections, and/or any drastic nonlinear path. The method increases the accuracy of the first position estimate (FPE) of the vehicle 102 outputted by the GPS processing system 700.

Detailed Description Paragraph Right (270):
The preferred embodiment implements the novel methodology of FIG. 20A via software. The software can be situated in the GPS processor 710 of the GPS processing system 700 at the vehicle 102 and/or at the base station 188.

Detailed Description Paragraph Right (271):
The flowchart 2000A begins at flowchart block 2001 and ends at flowchart block 2019. As shown in flowchart block 2005, the GPS processing system 700 as disclosed in FIGS. 7 and 8 computes the first position estimate using any of the bias techniques discussed previously in this document. In the preferred embodiment, the bias techniques subject to the method of FIG. 20A include, for example, the original bias technique of FIG. 15 and the parabolic bias technique of FIG. 16.

Detailed Description Paragraph Right (272):
At flowchart block 2009, a decision is made as to whether the vehicle 102 is approaching or is in the midst of a sharp corner, intersection, or other irregular path. The information needed to answer this question can be supplied to the GPS processor 710 from the navigator 406 of FIG. 4. If the answer to this question is in the negative, then the flowchart 2000A proceeds as indicated by an arrow 2013. In the alternative, that is, if the answer to this question is in the affirmative, then the flowchart 2000A proceeds as indicated by an arrow 2021. Both of these alternative avenues are discussed in detail below.

Detailed Description Paragraph Right (273):
When the vehicle 102 is not approaching or is not in the midst of a drastic nonlinear path, then the flowchart 2000A commences with flowchart block 2015. At flowchart block 2015, the GPS processor 710 outputs the first position estimate to the VPS 1000, which first position estimate was derived using one or more bias techniques. Recall that the VPS 1000, which is disclosed in FIGS. 10 and 11, calculates the third position estimate of the vehicle 102 using, in part, the first position estimate sent to it from the GPS processing system 700.

Detailed Description Paragraph Right (274):
When the vehicle 102 is approaching a drastic nonlinear path, then the flowchart 2000A commences with flowchart block 2023. At flowchart block 2023, the bias techniques are temporarily abandoned, until a more linear path ultimately ensues. The GPS processor 710 computes the first position estimate of the vehicle 102 without regard to the bias techniques, as indicated in flowchart block 2027.

Detailed Description Paragraph Right (275):
The flowchart next proceeds to flowchart block 2031. A determination is made as to whether the vehicle 102 is approaching or is in the midst of a relatively linear path. If so, then the flowchart 2000A returns to flowchart block 2005, as shown by a feedback arrow 2033. At the flowchart block 2005, any previously-terminated bias techniques are again instituted.

Detailed Description Paragraph Right (276):
In the case of the parabolic bias technique of FIG. 16, new best-fit parabolic models are constructed for each of the observed GPS satellites. Recall that actual pseudoranges are determined for each of the observed GPS satellites over a period of time to construct a parabolic model for each GPS satellite. The parabolic models are not utilized until the accuracy of the models is greater than a certain threshold. In the present invention, the parabolic models are not utilized until a statistical R.sup.2 value is greater than 0.99.

Detailed Description Paragraph Right (277):
Alternatively, if the vehicle 102 is not approaching or is not in the midst of a relatively linear path, then the flowchart 2000A moves to flowchart block 2015 discussed previously. However, it should be noted that the first position estimate transmitted to the VPS 1000 at this point was derived without regard to any bias techniques.

Detailed Description Paragraph Right (278):
It is believed that the U.S. government (the operator of the NAVSTAR GPS) may at certain times introduce errors into the GPS data being transmitted from the GPS satellites 132-170 by changing clock and/or ephemeris parameters. In other words, the U.S. government can selectively modify the availability of the GPS data. For example, such an action might take place during a national emergency. The U.S. government would still be able to use the NAVSTAR GPS because the U.S. government uses the other distinct type of pseudorandom code modulation, called the P-mode. Thus, the U.S. government could debilitate the C/A mode. Such debilitation could cause the GPS receiver 706 to compute incorrect actual and estimated pseudoranges, and thus, incorrect first position estimates. The anti-selective availability technique of the present invention is a way to detect and compensate for any misleading GPS data.

Detailed Description Paragraph Right (279):
Turning now to FIG. 21, a flowchart 2100 of the anti-selective availability technique is depicted. In the preferred embodiment, the anti-selective availability technique is performed in the GPS processor 710 of the host processing system 186. However, the technique could be implemented in the GPS processor 710 at the vehicle 102. The flowchart 2100 begins at a flowchart block 2102 and ends at flowchart block 2118.

Detailed Description Paragraph Right (280):
At a flowchart block 2104, estimated pseudoranges (predicted estimated pseudoranges; "Oij") of GPS satellites in view of the GPS antenna 702 are predicted by using old almanac data. Old almanac data is GPS data, or any part thereof, which has been previously recorded by the GPS receiver 706 and which enables the GPS processor 710 to compute predicted estimated pseudoranges without regard to the currently-received GPS data. In a sense, the old almanac data is used to check the integrity of currently-received GPS data. In the preferred embodiment, the old almanac data is the previous ephemeris which was received by the GPS receiver 706.

Detailed Description Paragraph Right (281):
With further reference to the flowchart block 2104, current estimated pseudoranges ("Nij") of the GPS satellites are computed in the usual fashion using the current ephemeris data (subset of GPS data) being transmitted by the GPS satellites and the base known position of the base station 188.

Detailed Description Paragraph Right (285):
Next, as shown at a flowchart block 2110, the base position estimate of the base station 188 is computed using the current time and either the currently received GPS data or the old almanac data (decided in flowchart block 2106).

Detailed Description Paragraph Right (287):

If the accuracy is within the preselected threshold, then the an indication is sent to the vehicle 102 that the GPS data is proper, as shown at a flowchart block 2116. As a result, the base station 188 forwards any information needed by the vehicle 102 in order to compute first position estimates. The information forwarded could include, for example, base clock biases, spatial biases (original biases, parabolic biases, base residuals biases), base estimated pseudoranges, and/or base actual pseudoranges.

Detailed Description Paragraph Right (288):
If the computed base station 188 is not within preselected threshold, then base clock biases and/or base spatial biases are manipulated so that the estimated base position is within the preselected threshold, as shown at a flowchart block 2114. The base clock biases needed to bring the base estimated position within the threshold of acceptability are then sent to the vehicle 102, as indicated at the flowchart block 2116.

Detailed Description Paragraph Right (289):
In addition to the determination of position estimates and navigation of the vehicle 102, the present invention can be used in a separate embodiment to accomplish surveying of the Earth 172's surface in real time. Thus, the position of any point on the Earth 172 can be computed using the techniques and methods of the present invention.

Detailed Description Paragraph Right (290):
The present invention provides for the production of graphic images on the user interface (not shown) of the host processing system 188. The graphic images allow human users at the base station 188 to view the paths of the vehicle 102 as well as any other vehicles which are being navigated with the present invention. In the preferred embodiment, the graphic images are displayed on commercially available video displays and, if desired, the screens can be printed by conventional printers.

Detailed Description Paragraph Right (291):
In considering implementation of an autonomous navigation system, there are some basic questions which any autonomous system must be able to answer in order to successfully navigate from point A to point B. The first question is "where are we (the vehicle) now? " This first question is answered by the positioning system portion of the present invention, as discussed above in section II.

Detailed Description Paragraph Right (292):
The next or second question is "where do we go and how do we get there? " This second question falls within the domain of the navigation system portion of the present invention, discussed in this section (III).

Detailed Description Paragraph Right (293):
A further (third) question, really a refinement of the second one, is "how do we actually physically move the vehicle, for example, what actuators are involved (steering, speed, braking, and so on), to get there? " This is in the domain of the vehicle controls subsystem of the navigation system, also discussed below.

Detailed Description Paragraph Right (294):
As has been discussed implicitly above, autonomous navigation, of a mining vehicle as an example, may provide certain significant advantages over conventional navigation. Among them is an increased productivity from round the clock, 24 hr. operation of the vehicles. The problems presented by dangerous work environments, or work environments where visibility is low, are particularly well suited to solution by an autonomous system.

Detailed Description Paragraph Right (295):
There are, for instance, some mining sites where visibility is so poor that work is not possible 200 days of the year. There are other areas which may be hazardous to human life because of being contaminated by industrial or nuclear pollution. An area may be so remote or desolate that requiring humans to work there may pose severe hardships or be impractical. The application of the present invention could foreseeably include extraterrestrial operations, for example, mining on the Moon, provided that the necessary GPS satellites were put in Moon orbit.

Detailed Description Paragraph Right (296):
In a typical application of the present invention, as shown in FIG. 3, with regard to the navigation of a mining vehicle at a mining site, there are three basic work areas: the load site, the haul segment, and the dump site. At the load site, a hauling vehicle may be loaded with ore in any number of ways, by human operated shovels for instance, controlled either directly or by remote control, or by autonomous shovels. The hauling vehicle then must traverse an area called the haul segment which may be only a few hundred meters or may be several km's. At the end of the haul segment is the dump site, where the ore is dumped out of the hauling vehicle to be crushed, or otherwise refined, for instance. In the present invention, autonomous positioning and navigation may be used to control the hauling vehicle along the haul segment. Autonomously navigated refueling and maintenance vehicles are also envisioned.

Detailed Description Paragraph Right (297):
Referring now to FIGS. 4 and 5, navigation of the AMT (Autonomous Mining Truck) encompasses several systems, apparatus and/or functions. The VPS 1000 subsystem of the overall AMT system as described above, outputs position data that indicates where the vehicle is located, including, for example, a North and an East position.

Detailed Description Paragraph Right (298):
Referring now to FIGS. 4 and 5, position data output from the VPS is received by a navigator 406. The navigator determines where the vehicle wants to go (from route data) and how to get there, and in turn outputs data composed of steer and speed commands to a vehicle controls functional block 408 to move the vehicle.

Detailed Description Paragraph Right (299):
The vehicle controls block then outputs low level commands to the various vehicle 102 systems, such as the governor, brakes and transmission. As the vehicle is moving towards its destination, the vehicle controls block and the VPS receive feed-back information from the vehicle indicative of, for example, any fault conditions in the vehicle's systems, current speed, and so on.

Detailed Description Paragraph Right (300):
Navigation also must include an obstacle handling (detection and avoidance) capability to deal with the unexpected. A scanning system 404 detects obstacles in the vehicle's projected trajectory, as well as obstacles which may be approaching from the sides and informs the navigator of these.

Detailed Description Paragraph Right (301):
The navigator may be required to then decide if action is required to avoid the obstacle. If action is required, the navigator decides how to avoid the obstacle. And after avoiding the obstacle, the navigator decides how to get the vehicle back onto a path towards its destination.

Detailed Description Paragraph Right (303):
Referring to FIG. 5, in the preferred embodiment of the present invention, as described above, both the VPS and the navigator are located on the vehicle and communicate with the base station 188 to receive high level GPS position information and directives from a host processing system 186, discussed below. The system gathers GPS position information from the GPS satellites 200-206 at the base station and on-board the vehicle so that commonmode error can be removed and positioning accuracy enhanced.

Detailed Description Paragraph Right (305):
The host at the base station may tell the navigator to go from point A to point B, for instance, and may indicate one of a set of fixed routes to use. The host also handles other typical dispatching and scheduling activities, such as coordinating vehicles and equipment to maximize efficiency, avoid collisions, schedule maintenance, detect error conditions, and the like. The host also has an operations interface for a human manager.

Detailed Description Paragraph Right (306):
It was found to be desirable to locate the host at the base station and the navigator on the vehicle to avoid a communications bottleneck, and a resultant degradation in performance and responsiveness. Since the host sends relatively high-level commands

and simplified data to the navigator, it requires relatively little communication bandwidth. However, in situations where broad-band communication is available to the present invention, this may not be a factor.

Detailed Description Paragraph Right (307):
Another factor in determining the particular location of elements of the system of the present invention, is the time-criticality of autonomous navigation. The navigation system must continually check its absolute and relative locations to avoid unacceptable inaccuracies in following a route. The required frequency of checking location increases with the speed of the vehicle, and communication speed may become a limiting factor even at a relatively moderate vehicle speed.

Detailed Description Paragraph Right (308):
However, in applications where maximum vehicle speed is not a primary consideration and/or a high degree of route following accuracy is not critical, this communication factor may not be important. For example, in rapidly crossing large expanses of open, flat land, in a relatively straight path, it may not be necessary to check position as often in the journey as it would be in navigating a journey along a curvaceous mountain road.

Detailed Description Paragraph Right (309):
Conceptually, the navigation aspects of the present invention can be arbitrarily divided into the following major functions:

Detailed Description Paragraph Right (311):
Autonomous vehicle navigation in accordance with the present invention, conceptually consists of two sub problems, path generation and path tracking, which are solved separately.

Detailed Description Paragraph Right (312):
Path generation uses intermediate goals from a high level planner to generate a detailed path for the vehicle 102 to follow. There is a distinct trade-off between simplicity of representation of such plans and the ease with which they can be executed. For example, a simple scheme is to decompose a path into straight lines and circular curves. However, such paths cannot be tracked precisely simply because of discontinuities in curvature at transition points of segments that require instantaneous accelerations.

Detailed Description Paragraph Right (313):
Following path generation, path tracking takes, as input, the detailed path generated and controls the vehicle 102 to follow the path as precisely as possible. It is not enough to simply follow a pre-made list of steering commands because failure to achieve the required steering motions exactly, results in steady state offset errors. The errors accumulate in the long run. Global position feedback 432 may be used to compensate for less than ideal actuators. Methods have been developed for the present invention which deviate from traditional vehicle control schemes in which a time history of position (a trajectory) is implicit in the plan specified to the vehicle 102.

Detailed Description Paragraph Right (314):
These methods are appropriately labeled "path" tracking in that the steering motion is time decoupled; that is, steering motions are directly related to the geometric nature of the specified path, making speed of the vehicle 102 an independent parameter.

Detailed Description Paragraph Right (315):
Referring now to FIG. 3, an autonomous vehicle 102 may be required to traverse a haul segment 320 to a dump site 322, and after dumping its load, traverse another haul segment to a service shop 324, under the direction of the host processing system 186. The host processing system 186 determines the vehicle 102's destinations, which is called "cycle planning." The determination of which routes to take to get to a desired destination must be accomplished by "route planning."

Detailed Description Paragraph Right (316):
"Route planning" is the determination of which path segments to take to get to a desired destination. In general, a route can be thought of as a high-level abstraction

or representation of a set of points between two defined locations. Just as one can say to a human driver "take route 95 south from Lobster, Me. to Miami, Fla.," and the driver will translate the instruction into a series of operations (which may include starting the vehicle 102, releasing the brake 4406, engaging the transmission 4610, accelerating to the posted speed limit, turning the steering wheel 4910, avoiding obstacles 4002, and so on), the autonomous navigation system of the present invention performs similarly. As used in the system of the present invention, a "route" is a sequence of contiguous "segments" between the start and end of a trip.

Detailed Description Paragraph Right (317):
An autonomous vehicle 102 may begin at any position in the sequence and traverse the route in either direction. A "segment" is the "path" between "nodes." A "node" is a "posture" on a path which requires a decision. Examples of nodes are load sites 3318, dump sites 322, and intersections 326.

Detailed Description Paragraph Right (321):
A segment is, therefore, a sequence of contiguous postures between nodes. All segments have a speed associated with them, which specifies the maximum speed with which the vehicle 102 is to traverse that segment. The navigator 406 can command slower speeds, if necessary, to meet other requirements.

Detailed Description Paragraph Right (322):
Determining which postures are required to define a path segment by analytical, experimental or a combination of both, is called "path planning" in accordance with the present invention. To bring the discussion full circle, a sequence of contiguous routes, as mentioned above, is referred to as a "cycle," and a vehicle 102's work goals determine its "cycle."

Detailed Description Paragraph Right (326):
The path-tracking method of the present invention (discussed below) uses route curvature to steer the vehicle. Methods of route definition using lines and arcs do not provide for continuous curvature. Clothoid curves are another way to define routes.

Detailed Description Paragraph Right (327):
Another method of defining routes developed by the inventors, fits B-splines to the driven data. B-splines provide continuous curvature and therefore enhance tracking performances. In addition, since B-splines are free form curves, a route may be defined by a single B-spline curve. By using free form curves, a more robust method (semi-automatic) for fitting routes to data collected by driving the vehicle over the routes is produced by the present invention.

Detailed Description Paragraph Right (328):
Referring to FIGS. 4 and 22, in operation, the host processing system 186 from the base station 188 commands an identified vehicle 102 to take route N from its present location. The navigator 406 functions to generate a path by translating "route 1" into a series of segments, each of which may have a "posted" or associated maximum speed limit, which together form a generated path for the vehicle to attempt to follow. By specifying routes and commanding the autonomous vehicle 102 with high-level commands this way, enormous data requirements and inefficiencies are in the present invention avoided in giving directions.

Detailed Description Paragraph Right (333):
As discussed above, part of the navigation problem addressed and solved by the present invention is really two sub-problems: path planning and path generation. These are solved separately by the present invention.

Detailed Description Paragraph Right (334):
Path planning proceeds from a set of sub-goals using some path optimization function and generates an ordered sequence of "objective" points that the vehicle 102 must attain.

Detailed Description Paragraph Right (335):
The challenge of path generation is to produce from the objective points (of path planning), a continuous, collision-free path 3312, smooth enough to be followed easily

by the autonomous vehicle 102. For example, a simple scheme is to decompose a path 3312 into straight lines and circular curves. The path 3312 is then converted into a sequence of explicit directives provided to the vehicle 102 actuators to keep the vehicle on the desired path 3312. It should be noted that there is a distinct trade-off between simplicity of representation of such plans and the ease with which they can be executed.

Detailed Description Paragraph Right (336):
The ability of an autonomous vehicle 102 to track a specified path 3312 is dependant on the characteristics of the path. Continuity of curvature and the rate of change of curvature (sharpness) of the generated path 3312 are of particular importance since these parameters dictate steering motions required of a vehicle 102 for it to stay on the desired path 3312. Discontinuities in curvature are impossible to follow since they require an infinite acceleration. For some autonomous vehicle configurations, the extent to which the sharpness of a path is linear is the extent to which steering motions are likely to keep the vehicle on the desired path 3312, since linear sharpness of a path equates to approximately constant velocity of steering.

Detailed Description Paragraph Right (341):
The quadruple of these parameters, p=(x,y,0,c), is a posture 3314 that describes the state of an autonomous vehicle 102 at any point in time.

Detailed Description Paragraph Right (344):
Practical navigation problems require composite paths whose range and complexity cannot be satisfied by a single clothoid segment. Most paths require multiple segments that pass through a sequence of objective points.

Detailed Description Paragraph Right (346):
An article by Hongo et al. entitled, "An Automatic Guidance System of a Self-Controlled Vehicle--The Command System and Control Algorithm", Proceedings IECON. 1985, MIT Press, 1985, proposed a method to generate continuous paths composed of connected straight lines and circular arcs from a sequence of objective points. While paths comprised solely of arcs and straight lines are easy to compute, such a scheme leaves discontinuities at the transitions of the segments as discussed above.

Detailed Description Paragraph Right (358):
Clothoid replanning is done either to acquire the path initially, or to guide the vehicle 102 back to the desired path 3312 through normal navigation according to the present invention.

Detailed Description Paragraph Right (362):
Reference is made to FIG. 28, which graphically illustrates replanning a path in accordance with the present invention. A pre-specified path consists of interpolations 2804 between postures (k,s).sub.m (m=1. . . , n) 2804-2810 and the postures P.sub.m (located at the end of segment (k,s).sub.m). Assuming that the vehicle 102 deviates from the path between P.sub.m and P.sub.m +1, then P.sub.m +2 is chosen as the posture 334 to which the replanned path 2816 converges. The distance to Pm+2 is variable.

Detailed Description Paragraph Right (364):
In accordance with the present invention, generation of continuous paths for autonomous vehicle 102 can use clothoid segments to generate paths not only because the resulting path is posture continuous but also because linear curvature along the curve leads to steering angles that vary approximately linearly along the path, facilitating path tracking.

Detailed Description Paragraph Right (368):
Advantages of the present invention's handling routes in this way, besides reducing the bandwidth requirements between the host and the vehicle, effects data compression reducing data storage requirements, and functions to smooth-out paths.

Detailed Description Paragraph Right (372):
In one embodiment of the present invention, in order to create routes for a site 300, data is first collected from the VPS 1000 and stored while a human drives the vehicle 102 over the road system of the work site 300. Nodes and segments are then fitted to the stored driven data, and organized into routes per the aforementioned procedure.

Detailed Description Paragraph Right (376):
In mining applications, generally a site 300 is surveyed and roads are pre-planned, carefully laid out and built. The routes used by the navigation system may then either be obtained from a manually created computer data base (created specifically to be used by the navigation system), or alternately, a vehicle may be physically driven over the actual routes on site to learn the routes as described above. In the learning method, several trips over a given route may be made. Then the variations in the data (due for instance to driver weaving) are averaged, and a smoothed-out best fit developed.

Detailed Description Paragraph Right (386):
A user simply tells the vehicle which item in the routeSpec array to use as a route.

Detailed Description Paragraph Right (390):
Next the operator specifies a route for the vehicle 102 to follow. Again, the route is simply an index into the routeSpec array.

Detailed Description Paragraph Right (392):
The vps.sub.-- posture task 5324 then determines the position, along the route which is closest to the vehicle 102's present position 2812. The search for the closest position 284 on the route proceeds as follows:

Detailed Description Paragraph Right (394):
2. The perpendicular distance from the vehicle position to the segment is determined.

Detailed Description Paragraph Right (396):
4. The perpendicular distance from the vehicle position to the next segment is determined.

Detailed Description Paragraph Right (398):
6. Determine the distance from the vehicle position to the end points 2218 of the route.

Detailed Description Paragraph Right (406):
AS the autonomous vehicle 102 moves along the posture in the buffer 3000, the safety margin 3006 is depleted. When the safety margin is below a specified amount, the vps.sub.-- posture task 5324 generates another safety margin 3006 of postures and appends them to the current buffer 3000. The vps.sub.-- posture task 5324 depletes the posture buffer 3000 by monitoring the current position 2812 of the vehicle 102 and moving a pointer 3002 in the buffer 3000 to the nearest posture. The posture buffer 3000 is constructed as a ring which is traversed in the clockwise direction (see FIG. 30, Posture Ring Buffer). That is, postures are placed in the ring such that the direction of vehicle travel corresponds to a clockwise traversal of the posture ring buffer 3000. Therefore, as the vehicle 102 moves the pointer 3002 to the nearest posture in the buffer 3000 will be moved in the clockwise direction. When the pointer 3002 will be moved in the clockwise direction, memory in the ring behind posture (counterclockwise of the pointer) is free to be over written.

Detailed Description Paragraph Right (411):
The task which produces the postures reads the current position of the vehicle 102, finds the nearest point on the route to the current position, then generates a specified number of postures ahead of the vehicle 102. The number of postures generated is dependent on the maximum stopping distance of the vehicle 102. That is, there should always be enough postures in the buffer 3000 to guide the vehicle 102 to a stopping point.

Detailed Description Paragraph Right (413):
Path tracking or following is a critical aspect of vehicle navigation according to the present invention. The technique of the present invention uses position based navigation (rather than vision based navigation used in conventional navigation systems) to ensure that the correct autonomous vehicle path 3312 is followed. The present invention is also innovative in that it provides for separate control of steering angle 3116 and vehicle speed 3118. FIG. 36 graphically illustrates the path tracking system 3102 of the present invention.

Detailed Description Paragraph Right (414):
For an autonomous vehicle 102 according to the present invention to track specified paths, it is necessary to generate referenced inputs for the vehicle servo-controllers. Thus, path tracking can be considered as a problem of obtaining a referenced steering angle and a reference speed for the next time interval in order to get back to the referenced path ahead from the current deviated position.

Detailed Description Paragraph Right (415):
In general terms, path tracking is determining the autonomous vehicle commands (speed, steer angle) required to follow a given path. Given a pre-specified steering angle, driven wheel velocity values and error components, the command steering and driving inputs are computed in the present invention.

Detailed Description Paragraph Right (416):
The path to be tracked is specified in Cartesian coordinates. If the control scheme consists of only a servo-control to reference steering commands, vehicle position and heading errors accumulate. Position and heading result from integrating the whole history of steering and driving. Thus, it is necessary to feedback vehicle position 3304 and heading 3318 in Cartesian space.

Detailed Description Paragraph Right (418):
Steering and driving reference inputs are computed in the present invention, from the given path and vehicle speed, respectively. This enables easy integration of path tracking with other modules of the present invention, such as collision avoidance.

Detailed Description Paragraph Right (419):
One of the challenges of vehicle autonomy is to determine the steering inputs required to track a specified path. For conventionally steered vehicles, in the present invention the desired path and the desired speed along the path can be tracked separately, reducing the problem to one of controlling the steering. (A path, for this discussion, being a geometric curve independent of time in contrast to a trajectory, which is a time history of positions.)

Detailed Description Paragraph Right (420):
Steering angles are planned from the desired path 3312 and sensed vehicle positions. These angles are commanded to the vehicle via a steering controller 3104.

Detailed Description Paragraph Right (423):
In a manually driven vehicle, the look-ahead distance is the distance 3310 in front of a vehicle that a driver looks during driving. The look-ahead distance in the present invention, is the distance by which the errors in position, heading and curvature are planned to be reduced to zero. It varies with the speed of the conventional or autonomous vehicle.

Detailed Description Paragraph Right (425):
However, real vehicles depart from kinematic idealization, and their control response departs accordingly. As vehicle speed, mass and path conditions change, actual vehicle response departs even further from kinematic idealization. Hence, kinematic idealization is generally valid only at low speeds with constant conditions.

Detailed Description Paragraph Right (426):
An embodiment of the present invention uses a model which includes considerations of cornering stiffness, mass and slip angle. The control problem is formulated as a linear quadratic optimal tracking problem where the errors in position, heading and curvature are minimized based on the vehicle control model.

Detailed Description Paragraph Right (427):
The optimal path and controls are computed from the desired path 3312 and the currently sensed vehicle position using the current errors as initial conditions to the optimal control problem. A few computed steering angles along the initial part of the optimal path are used as references to the low level steering controller for the next sensing time interval.

Detailed Description Paragraph Right (428):

This preview optimal steering planning has the advantage of guaranteeing stability and optimality with respect to the given performance index. The optimal preview control method of the present invention is central to the steering planning of an autonomous vehicle.

Detailed Description Paragraph Right (432):
Significantly, as mentioned above, these vehicle and path techniques of the present invention, decouple steering control from velocity control at the vehicle.

Detailed Description Paragraph Right (435):
If the desired path is considered as a continuous function of position and the vehicle is currently at Pa 3320, an error vector can be calculated (FIG. 33) that represents error in the distance transverse to the path (eO) 3322 relative to Po 3304, in heading (Bo) 3322, and in curvature (yo) 3404. If the vehicle is to be brought back onto the specified path within distance L 3310 (measured along the reference path), six boundary conditions can be stated corresponding to the initial errors and to zero errors at PL. ##EQU7##

Detailed Description Paragraph Right (437):
The expression for e(s) gives the error along the replanned path 2816 from Po 3304 to PL 3308. The second derivative describes path curvature, which can in turn, be used to calculate a steering command to guide the vehicle back to the desired path 3312. Variation in the steering angle 3116 from the replanned path 2816 (or in error space) is computed from the second derivative of error function e(s). Then, curvature along the new path can be computed as: ##EQU8##

Detailed Description Paragraph Right (439):
The look-ahead distance, L 3310, is a parameter that can be used to adjust how rapidly the vehicle steers to converge to the desired path. Additionally, better performance is obtained if L 3310 is chosen proportional to the vehicle speed because for small values of L 3310, the vehicle oscillates around the path 3312, while for large values of L 3310 the variation introduced by the quintic polynomial is small enough that the tracking performance is poor.

Detailed Description Paragraph Right (441):
Recall that path tracking schemes in general, perform better when the path specified is intrinsically easier to track. This is especially the case when the steering actuators are slow compared to the speed of the vehicle.

Detailed Description Paragraph Right (442):
Other vehicle characteristics, like steering response, steering backlash, vehicle speed, sampling, and planning time intervals significantly affect vehicle performance. As expected, at higher vehicle speeds, faster and more accurate actuators are necessary, if sensing and planning time intervals are kept constant.

Detailed Description Paragraph Right (443):
An advantage of the quintic polynomial method in general, is that it is simple, and reference steering angles can be computed very easily. However, since there is no consideration of vehicle characteristics (mass, inertia, time delays, vehicle ground interaction, and so on) in the control scheme, stability and convergence are not guaranteed.

Detailed Description Paragraph Right (444):
The parameter L 3310 (look-ahead distance) can be adjusted to modify response to the vehicle, and the value of L 3310 can be chosen based on trial and error. This scheme has provided good results at speeds up to approximately 28 Km per hour at the time this application disclosure was prepared.

Detailed Description Paragraph Right (446):
An additional path tracking embodiment of the present invention uses various compensation techniques to improve vehicle response characteristics. This is used in conjunction with the quintic polynomial method to realize improved tracking performance.

Detailed Description Paragraph Right (447):

Some vehicle response characteristics include latency of vehicle control commands, slow system response, and vehicle dynamic characteristics including vehicle-ground interaction (VGI), (slip angle and under/over steer).

Detailed Description Paragraph Right (448):
The latency of vehicle commands was compensated in one embodiment of the present invention, by modifying the vehicle control hardware to reduce time delays, and by utilizing a method which sets control commands far enough in advance to compensate for the existing delays.

Detailed Description Paragraph Right (449):
Decreasing the time lag between when the vehicle position is sensed and when the command is issued reduces prediction errors, which reduction is required to plan steering angles, and results in better tracking performance.

Detailed Description Paragraph Right (451):
A tracking method outputs steering and speed commands over a serial link to a vehicle control system. The vehicle control system is a multi-processor, multi-tasking system, relying on a mailbox queue for communication between tasks.

Detailed Description Paragraph Right (454):
To resolve the latency and response problems, hardware may be adjusted to be used in close conjunction with the tracking method to control vehicle steering, and a new control scheme devised to compensate for pure time delay and poor response.

Detailed Description Paragraph Right (455):
The hardware may be adjusted, for example, to reside on the same back plane as the processor which executes the tracking method and controls the vehicle steering system directly. This serves to eliminate delays due to the serial link and queuing.

Detailed Description Paragraph Right (465):
Reference commands for steering angle and vehicle speed result in varying angular velocities and accelerations of the vehicle wheels.

Detailed Description Paragraph Right (466):
VGI describes how the vehicle moves, given steered wheel angles and wheel angular velocities. The principal VGI phenomena are slip angle and under/oversteer characteristics which are based on the tire/road contact region geometry, and are affected by tire elastic deformation. These phenomena require a larger steering angle as compared to a kinematically computed one.

Detailed Description Paragraph Right (468):
At times, especially when the discrete time interval is large, poor predictions of the vehicle position may be made which degrade performance of the tracking method.
##STR1##

Detailed Description Paragraph Right (469):
A compensation method of the present invention, serves to reduce the error in predicting the next vehicle position by decreasing the discrete time interval. In this method, the vehicle position is predicted for the end of the computing interval (16 mSec) rather than at the end of the planning interval (250 mSec). The method is executed as follows:

Detailed Description Paragraph Right (477):
Human operators use different look-ahead distances 3310 when driving. At slow speeds, a driver generally looks at a point on the road relatively close to the vehicle, while at higher speeds, this point is generally farther ahead of the vehicle. The higher the speed, the farther ahead the reference point is, resulting in smaller steering corrections.

Detailed Description Paragraph Right (479):
A desired steering angle may consist of a steering angle from the reference path 3312 and a steering angle 3112 which is computed with a quintic method to correct for tracking errors. These steering angles are summed to give the vehicle steering command as shown in equation (1) below:

Detailed Description Paragraph Right (483):
The control problem is formulated as a linear quadratic optimal tracking problem where the errors in position, heading and curvature are minimized based on the vehicle control model. The optimal path and controls are computed from the desired path 3312 and the currently sensed vehicle position 3304 using the current errors as initial conditions to the optimal control problem.

Detailed Description Paragraph Right (484):
A few computed steering angles along the initial part of the optimal path are used as references to the low level steering controller for the next sensing time interval. This preview optimal steering control has the advantage of guaranteeing stability and optimality with respect to the given performance index. The optimal preview control method according to the present invention, is applicable to the steering planning of an autonomous vehicle 102.

Detailed Description Paragraph Right (485):
The model is derived from a standard telescoped, or bicycle model (not shown) or approximation of the vehicle. The equations describing the vehicle motion include terms which represent the VGI described earlier. These equations use the state variables:

Detailed Description Paragraph Right (491):
3. The first term inside the integration (within the above cost function) is the time derivative of the control input, which is not usual in a quadratic cost function of an optimal control problem. However, the time rate change of steering is very important for smooth path following, because it is directly related to the time rate of change of centrifugal force (due to lateral accelerations of the vehicle).

Detailed Description Paragraph Right (494):
1. Since the sinusoidal functions in the first and the second equations of (14) make the system nonlinear, a new coordinate system, an axis of which is parallel to the tangent direction of the corresponding point of the path to the current vehicle position, is used. The deviations only in the lateral direction are considered in the cost function. These two approximations not only eliminate the nonlinearity in the system equation but also reduce the number of equations to deal with; the first equation of (14) is not required now. (Refer to "Coordinate Systems.")

Detailed Description Paragraph Right (506):
Tracking performance has been improved according to the present invention, by investigating and understanding vehicle and control system dynamics and by designing compensation methods given this understanding.

Detailed Description Paragraph Right (507):
A degraded performance of a tracking method is attributable to latency of vehicle control commands, slow system response, and vehicle dynamic characteristics. It is possible to counteract each of these effects.

Detailed Description Paragraph Right (508):
Latency of Vehicle commands, a dominant effect, can be successfully compensated by modifying the vehicle control hardware and by utilizing a method which set control commands far enough in advance to compensate the delays. Decreasing the time lag between when the vehicle position is sensed and when the command is issued reduces prediction errors. This iS required to plan steering angles, and results in better tracking performance.

Detailed Description Paragraph Right (510):
In general terms then, path tracking is the function of staying on course. In path tracking in the present invention, as discussed, some of the considerations are errors in distance, heading and curvature, delays in the system including processing delays and delays in vehicle response to actuators, and so on, dynamic look ahead distance, weighted path history, and extrapolation.

Detailed Description Paragraph Right (512):
In addition to path tracking (following), successful navigation of vehicle 102

requires that vehicle 102 be able to detect obstacles 4002 in its path, thus allowing the vehicle to stop or otherwise avoid such an obstacle before a collision occurs.

Detailed Description Paragraph Right (514):
Since a reference path 3312 is available and the vehicle position is known relative to the reference path, only the range data and a region bounding the reference path 3312 is processed for threatening objects 4002. Objects outside of this region, or boundary zone, are ignored. The width of the boundary zone (not shown) is equal to the vehicle width plus some selected safety buffer to allow for tracking and positioning errors. This method is limited in its usefulness and is referred to as "clearance checking."

Detailed Description Paragraph Right (517):
A second obstacle detection embodiment of the present invention uses a multiple-line scanner 3804 (See FIG. 38), whose scan 3810 contacts the ground at some distance in front of the vehicle 102. Since the scan line contacts the ground, discontinuities in range data can no longer be attributed to threatening objects 4002. For example, profiles from natural objects such as hills and banked or crowned roads can cause discontinuities in range data. This technique of the present invention can discern discontinuities in range data between threatening objects 4002 and natural objects (not shown).

Detailed Description Paragraph Right (519):
Processing load is minimized by selecting a relatively small number of the scan lines available in a range image representation 3900. The scan lines are selected by vehicle speed, and are concentrated at, and beyond, the vehicle stopping distance. The selected scan lines from successive frames of data can overlap.

Detailed Description Paragraph Right (520):
In this method, if the vehicle 102 is moving fast, the selected scan lines 3906 are far in front of the vehicle (near the top of the range image representation 3900). In contrast, when the vehicle is traveling slowly, the selective scan lines 3906 are closer to the vehicle (near the bottom of the range image representation 3900).

Detailed Description Paragraph Right (521):
Each scan line is made up of many pixels of data. Each pixel has two parameters associated with it. First, the actual value of the pixel is the range value returned by the scanner 3804. Second, the location of the pixel on the scan line gives an indication of the angle, relative to the vehicle centerline, at which the range value was recorded. This corresponds to a cylindrical coordinate frame (R,THETA,Z) description.

Detailed Description Paragraph Right (522):
Given the cylindrical description and the known scanner location with respect to the vehicle 102, the range values can be converted to a Cartesian coordinate (X,Y,Z) system. The result is a road profile description which can be used by a novel filtering scheme to determine if threatening objects 4002 are present in the vehicle path 3812, while ignoring effects due to natural hills and valleys in a typical roadway.

Detailed Description Paragraph Right (523):
After the scanner data is converted to Cartesian coordinates, the data is processed to determine which part of the scan is actually on the road 3312 and which part of the scan line is outside of the vehicle path and therefore safely ignored. Given the vehicle position and the width of a boundary (which is equal to the vehicle width plus some safety margin), the coordinates of the boundary on either side of the vehicle path can be determined. The coordinates of the boundary can be compared to the coordinates of each pixel on the current scan line. The pixels which have coordinates outside of the boundary are ignored.

Detailed Description Paragraph Right (536):
Assuming that the vehicle path 3812 is specified at regular intervals, the current vehicle position can be used to locate the path segment line 3902 in front of the scanner. This path 3812 is transformed from world coordinates into image coordinates by projecting the points corresponding to the road or boundary edges 3902 into the image plane (see FIG. 39).

Detailed Description Paragraph Right (545):
Once the present invention detects an obstacle 4002 in the path of the vehicle 102 (See FIG. 40), it must then avoid a collision with the object. Certain assumptions are made concerning the obstacle avoidance problem:

Detailed Description Paragraph Right (547):
First, to decide if any obstacles are in the way, and if so, which side should the vehicle pass on. Then select a sub-goal 4006, which will lead the vehicle 102 around the obstacle 4002, leading towards a higher level goal 4008, which is to get back on the desired path.

Detailed Description Paragraph Right (548):
Second, once a sub-goal 4006 is selected, make a steering decision which drives the vehicle 102 towards the sub-goal 4006, while steering clear of the obstacle 4002. A sub-goal selection method and a steering decision method of the present invention solve these two sub-problems.

Detailed Description Paragraph Right (550):
The obstacle locations are obtained from the laser range scanner 3804 or 404. The range data generated by the scanner 3804 or 404 are processed to produce a list of polygonal faces, modeling the visible portions of the obstacle 4002 from the vehicle position. Each time new range data become available, a sub-goal selection method is executed to generate a sub-goal 4006 and determine regions of safe navigation (free-space 4010) for the steering decision method. The frequency at which the sub-goal selection method can be executed depends on the rate at which the scanner 3804 or 404 can collect data. The achievable vehicle speed, in turn, depends on this frequency of execution.

Detailed Description Paragraph Right (556):
Given a flowchart blocking obstacle, there are two possible ways of going around it. If both edges of the obstacle are in the range of the scanner 3804 or 404, we may choose to go around the edge which gives the minimum sum of the distances from the vehicle 102 to edge and from the edge to the final distance. If only one edge of the obstacle 4002 is in the range, choose that edge to go around. If none of the edges is visible, always arbitrarily choose the left edged to go around. Once the edge to go around is determined, place the initial subgoal away from the edge at a distance that is proportional to the vehicle size.

Detailed Description Paragraph Right (557):
Because of this displacement, the resulting subgoal may be blocked by other obstacles 4002. This calls for the recursive generation of subgoal on the obstacle, which blocks the line of sight to the subgoals just generated. This recursive process continues until a subgoal visible to the vehicle 102 is generated. Each subgoal so generated is checked for viability. By viability it is meant that the subgoal does not lead the vehicle 102 towards a gap between two obstacles 4002 which is too small for the vehicle to pass through. When such a condition is detected, the vehicle 102 will stop.

Detailed Description Paragraph Right (558):
The direct subgoal generated in the second step (step 2 above) could possibly be obscured from the vehicle 102. If such is indeed the case, the old subgoals from the previous iteration is restored and used next (step 4 above).

Detailed Description Paragraph Right (562):
The present invention includes a method, as shown diagrammatically in FIG. 40, whereby a safe path around a detected object 4002 will be plotted and navigated so that the vehicle 102 will reacquire the reference path after avoiding the object 4002.

Detailed Description Paragraph Right (563):
Referring to FIGS. 38 and 42, the present invention also includes a laser scanner system 404. The scanner 404 is used to find obstructions 4002 (See FIG. 40) that randomly crop up in the vehicle 102 path, as previously discussed.

Detailed Description Paragraph Right (564):

Sources of such obstructions 4002 may be varied and numerous depending on the particular work site. They may include fallen trees and branches, boulders, moving and parked vehicles, and people.

Detailed Description Paragraph Right (565):
The scanner 404 gives the autonomous vehicle 102 the ability to detect and deal with the external world as conditions require.

Detailed Description Paragraph Right (572):
The second function is to disable the laser 4204 from firing for part of the 360 degrees scan area. Typically, the laser scanner unit 404 will be mounted in front of a vehicle 102, and the field of interest is in the 180 degree area in front of the vehicle. The vehicle itself will block the back portion of the 360 degree scan area. In this case, the circuitry 4228 will prevent the laser 4204 from firing into the vehicle, extending the life of the laser diode while receiving range data for the area in front of the vehicle. The enabling and disabling of the laser range-finder 4204 is done through two sensors (not shown) mounted near the mirror housing 4222. For testing purposes, or for applications where a 360 degree scan is desirable, the disable feature can be turned off through a DIP switch.

Detailed Description Paragraph Right (586):
Referring now to FIG. 43, the vehicle controls are comprised of four, low-level functional blocks.

Detailed Description Paragraph Right (587):
One is called a "vehicle manager" (4302). A second is called a "speed control" (4304). The third is called a "steering control" (4306). The fourth is called a "monitor/auxiliary control" (depicted as two separate blocks 4310 and 4308. These are described in turn below.

Detailed Description Paragraph Right (590):
While each functional block has a more or less specific function, the vehicle manager 4302 functions as a communications hub. It sends to and receives messages from the navigator 406 via an RS-422, 9600 Baud serial link 4316. It is also listening to and sending to the remote control or "tele" panel 410 via an FM radio communications link 4318.

Detailed Description Paragraph Right (591):
As mentioned above, the vehicle manager 4302 receives commands from a remote control panel 410 and the navigator 406. It then decides which mode "A, M, T, or R" (for Autonomous, Manual, Tele, or Ready) the vehicle 102 should be in.

Detailed Description Paragraph Right (592):
Reference is now made to FIG. 44, which shows the states (modes) and how the vehicle 102 changes between states. The navigator 406 cannot set the mode itself. Notice that the vehicle 102 cannot change from tele to auto, for instance, directly. It must pass through the ready mode 4404 first in that case.

Detailed Description Paragraph Right (593):
The ready mode 4404 brings the vehicle 102 to a stop in a known state. This is because it would be difficult to make a smooth transition, from, for instance, auto mode 4408 to tele mode 4406 while the vehicle 102 was moving. The tele control panel joystick 4502, 4504 would have to be in just the right position when control was switched.

Detailed Description Paragraph Right (594):
Going from tele 4406 to auto 4408 mode, there is the consideration that the navigator 406 must initialize. For example, it must determine where it is with respect to a route before taking control, which takes some finite time, during which the vehicle 102 might otherwise drive off uncontrolled.

Detailed Description Paragraph Right (595):
Tele control mode 4406, also referred to as tele-operation, remote control or radio control mode, provides a way of controlling the vehicle 102 from a remote location while the vehicle 102 is kept in view.

Detailed Description Paragraph Right (596):
Shop personnel would use the tele-operation mode 4406 to move the vehicle 102 in the yard, for example. Advantageously, this mode would also be used by a shovel or loader operator to maneuver the vehicle into position for loading or unloading, and moving the vehicle into a location where autonomous mode 4408 would resume control.

Detailed Description Paragraph Right (597):
In tele-operation mode 4406, each vehicle 102 at an autonomous work site 300 would have its own unique identification code that would be selected on a radio control panel 410 to ensure communication with and control of the correct vehicle only. The vehicle 102 would only respond to tele-operation commands 4318 when its unique identification code is transmitted. Any conflict between modes, such as between manual 4402 and tele 4406, would be resolved in favor of manual mode 4402, for obvious safety reasons.

Detailed Description Paragraph Right (598):
The navigator 406 keeps track of where the vehicle 102 is while being operated in the tele mode 4406, even though, in tele mode, the vehicle can be maneuvered far off of a known route.

Detailed Description Paragraph Right (599):
Manual control mode 4402 may be required when the vehicle 102 is being maneuvered in very close quarters, for example, at a repair shop, equipment yard, and so on, or when a control subsystem needs to be removed for repair or maintenance.

Detailed Description Paragraph Right (601):
While in manual mode, the autonomous system would continuously monitor vehicle motion and maintain an updated record of the vehicle position so that when and if autonomous mode 4408 was desired, a quicker and more efficient transition could be made.

Detailed Description Paragraph Right (602):
When autonomous mode 4408 is again desired, the human operator would then affirmatively act to engage autonomous mode 4408, by physically moving a switch or lever, for instance, to the autonomous control mode. A time delay would preferably be built in so that the human operator would have the opportunity to leave the vehicle 102 if desired. At the end of the time delay, the system would then give several levels of warning, such as lights, horn, or the like, indicating autonomous takeover of the vehicle 102 was imminent.

Detailed Description Paragraph Right (603):
The autonomous mode 4408 is entered into from ready mode 4404. In the autonomous mode 4408, the vehicle 102 is under the control of the autonomous navigation system.

Detailed Description Paragraph Right (604):
In this mode, the vehicle control system receives messages from the navigator 406 as discussed above, through the vehicle manager 4302. The vehicle manager 4302 is, as discussed, basically the communications and command hub for the rest of the controllers.

Detailed Description Paragraph Right (605):
The vehicle manager 4302, and the other functional control blocks, all communicate with the shutdown circuits 4312 as well. The shutdown circuits 4312 are discussed in more detail below.

Detailed Description Paragraph Right (606):
The speed control subsystem 4302 may be organized to contain a speed command analyzer, closed loop controls 4800 for the engine 4614, transmission and brakes 4700, 5000, a real time simulation model of the speed control system, and a monitor 4310 that is tied to an independent vehicle shutdown system 4312. It is designed to be placed in parallel to the production system on the vehicle 102.

Detailed Description Paragraph Right (609):
The autonomous system speed control block 4304 feeds the transmission control block 4616 the maximum gear desired. For instance, if the vehicle 102 is to go 15 mph, the maximum gear might be third gear. The production transmission control block 4616 will

control all the shifting necessary to get to that gear appropriately.

Detailed Description Paragraph Right (612):
The following discusses vehicle systems shown in FIGS. 46, 48, 47, 50 and 49. These systems relate to the vehicle drive train 4600 and steering 4900 systems.

Detailed Description Paragraph Right (613):
Referring to FIG. 46 a governor 4626 controls engine speed 4222, which in turn controls vehicle speed 4624. The engine power is transferred to the drive wheels through the drive train 4600 which is comprised of:

Detailed Description Paragraph Right (614):
Several key systems were modified in accordance with the present invention to effect autonomous control. The primary systems were the speed control (engine speed, transmission, vehicle speed, and brakes) and steering systems. Each key system is design with manual override capability as a safety measure. In all cases, manual control has priority so that if the vehicle is operating autonomously, and an operator takes control of any one of the vehicle functions, control automatically is returned to the operator.

Detailed Description Paragraph Right (615):
The system also provides an emergency override button (not shown; also referred to as a `panic` button) which, when activated, disables all electronically controlled systems and returns the vehicle 102 to manual control 4402.

Detailed Description Paragraph Right (616):
The system also provides for sensing the pneumatic pressure which is a key part for actuating some of the key systems. If this pressure falls below some preset threshold, it is assumed that there is a problem and the vehicle control system reverts to manual control 4402 and the vehicle 102 is stopped.

Detailed Description Paragraph Right (618):
Also required to control the vehicle speed is a transmission control 4616. The basic control system is readily available on the particular vehicle used for this purpose.

Detailed Description Paragraph Right (619):
In addition to controlling the engine speed 4622 as a means of regulating vehicle speed, it is also necessary to control the vehicle service brakes 4606. This system is shown in FIG. 47 and is necessary to effect normal stoppage or slowing of the vehicle 102. This system uses electronically controlled pneumatic valves 4712 and 4716 in parallel with a manually operated brake pedal 4708 and/or retarder lever 4710 to regulate the braking force. These two manual inputs can override the electronic control system when actuated. The pressure sensor 4702 and the vehicle speed sensor 4624 provide the necessary feedback to regulate the braking force.

Detailed Description Paragraph Right (620):
Control of vehicle steering is also required for the vehicle to operate autonomously. The system which performs this function is shown in FIG. 49. The system consists of a Rexroth proportional hydraulic valve 4912 which can be actuated electronically to provide flow to hydraulic cylinders 4914 and 4916 attached to the vehicle steering linkage. The system also comprises a manually operable hand-metering unit, or HMU, 4918, which is in parallel to the electronically controlled system. The manual system can override the electronic system, if required, as a safety measure. Also, the system provides a switch 4920 on the HMU to detect when the manual steering wheel 4910 is different from the centered position. When not centered, the autonomous system assumes that the system is being operated manually 4402 and disables autonomous control of the vehicle 102.

Detailed Description Paragraph Right (621):
Electronic control of the vehicle parking brake is also included as an added safety feature. This system is shown in FIG. 50. For proper operation under autonomous control, the parking brake is manually placed in the `ON` position. When the vehicle proceeds through the status modes (MANUAL 4402, READY 4404, and AUTO 4408), the parking brake is automatically released by electronically controlling the pneumatic valve 5008. This system is in parallel to the manual systems comprised of the brake

lever release valve 5016 and the Emergency brake lever 5014.

Detailed Description Paragraph Right (622):
When a problem is encountered, the vehicle 102 is automatically placed under manual control. Since the manual setting of the park brake is normally `ON` this activates the parking brake, stopping the vehicle 102 as quickly as possible.

Detailed Description Paragraph Right (623):
Referring again to FIG. 43, the steering control functional block 4306 is responsible for controlling the steer angle of the vehicle's wheels. It sends out commands to a valve 4912 to control the steer angle and receives information from a resolver (not shown) mounted on the tie rod system, so that it knows what the actual wheel angle is.

Detailed Description Paragraph Right (625):
At some point in the useful life of the vehicle 102 the resolver may go out of adjustment. If this happens, the vehicle will not be able to track the path 3312 properly.

Detailed Description Paragraph Right (626):
However, the navigator 406 constantly monitors the vehicle 102 to determine how far the vehicle 102 is from the desired path 3312. (The vehicle 102 is always off the desired path 3812 to some extent, and the system is constantly correcting.) If the vehicle 102 is more than a certain distance, for example several meters, from the desired path 3312, the navigator 406 stops the vehicle as a safety precaution.

Detailed Description Paragraph Right (628):
The autonomous steering system 4900 may be designed to be implemented in parallel with a manual steering system, and can be retro-fitted on to the vehicle 102 in a similar manner as the speed control system.

Detailed Description Paragraph Right (632):
Of course a vehicle 102 may be manufactured without any manual steering system at all on the vehicle if desired. To drive the vehicle manually, the tele-panel 410 could be used, or some sort of tele-panel might be plugged into the side of the vehicle 102 to control it without a radio link 4506 in close quarters, for instance. A jump seat might be provided for an operator in such situations.

Detailed Description Paragraph Right (634):
The basis for the steering planner is a tricycle steering model shown in FIG. 5.1. This model permits the calculation of the required steer angle independent of the velocity of the vehicle.

Detailed Description Paragraph Right (637):
Referring to FIGS. 22-34, the response of autonomous vehicle 102 in tracking a path 3312 depends partly on the characteristics of the path 3312. In particular, continuity of the curvature and the rate of change of curvature (sharpness) of the path 3312 are of particular importance, since these parameters govern the idealized steering motions to keep the vehicle 102 on the desired path 3312. In the case where a path 3312 is specified as a sequence of arcs and lines, there are discontinuities of curvature at the point where two arcs of differing radii meet. Discontinuities in curvature are troublesome, since they require an infinite acceleration of the steering wheel. A vehicle travelling through such transition points with non-zero velocity will experience an offset error along the desired path 3312.

Detailed Description Paragraph Right (638):
In general, and as shown in FIG. 33, if a posture 3314 is desired as the quadruple of parameters--position 3320, heading 3318, and curvature 3316 (x, y, O, c), then it is required that the path 3812 be posture-continuous. In addition, the extent to which steering motions are likely to keep the vehicle 102 on the desired path 3312 correlates with the linearity of sharpness of the path, since linear curvature along a path means linear steering velocity while moving along the path.

Detailed Description Paragraph Right (643):
The steering planner calculates the steer angle needed to follow the desired path. If

the vehicle 102 was on the desired path 3312, the steer angle is:

Detailed Description Paragraph Right (644):
If the vehicle 102 is off the desired path 3312, then the steer angle is:

Detailed Description Paragraph Right (651):
Referring now to FIG. 43, the monitor/auxiliary functional block(s) 4308 and 4310 take care of some miscellaneous functions not performed by the other blocks of the vehicle control system. For instance, start or kill the engine 4616, honk the horn, raise or lower the bed, setting the parking brake on or off, turning the lights on or off, are some of its functions.

Detailed Description Paragraph Right (653):
The safety system, including shutdown circuits 4312, (see FIGS. 43 and 52) operates to stop the vehicle 102 on detection of a variety of error conditions by setting the parking brake on. This results in the vehicle 102 coming to a safe stop in the shortest distance possible.

Detailed Description Paragraph Right (655):
Whenever several erroneous commands are received, or whenever the speed and/or steering simulation models disagree beyond an acceptable tolerance with vehicle sensor outputs 4622 and 4624, are examples of conditions which could result in shutdown of the system. The shutdown system 4312 is an independent and separate subsystem from the other autonomous control subsystems (see FIGS. 43 and 52).

Detailed Description Paragraph Right (656):
The safety system shutdown circuits 4312 shown in FIG. 43 connected to receive the outputs of the other vehicle control system functional blocks is shown in more detail in FIG. 52.

Detailed Description Paragraph Right (658):
A feature of the vehicle control system 4312 design is that all functional blocks are capable of detecting errors in the output of the others on the serial bus 4314. So if one of them senses that another is not functioning correctly, it can send a signal to the shutdown circuits 4312 to shut the system down.

Detailed Description Paragraph Right (659):
For example, the speed and steering blocks each look at their received commands (received via the vehicle manager 4302) to make sure they are valid. They also make sure that what they are told to execute, that is, what they are requested to command, is within predetermined bounds. If not, they will act to shut the system down.

Detailed Description Paragraph Right (660):
The safety system may also be monitoring oil, hydraulic and pneumatic pressures, and temperatures, for instance, making sure they are sufficient to safely operate and control the vehicle.

Detailed Description Paragraph Right (662):
The bus 4314 that inter-connects the vehicle control system functional units 4302, 4304, 4306, 4308, and 4310 is a serial data type common bus implemented in a ring structure using a data packet collision detection scheme.

Detailed Description Paragraph Right (665):
This task 5308 is shown above and to the right of the "main" task 5316. It functions to read the vehicle port 5326, and report vehicle mode changes and navigator-to-vehicle communication state to the "main" 5316 via the EXEC QUEUE 5328. Additionally, the status of the vehicle 102 is written to a global memory structure 5400 (see FIG. 54).

Detailed Description Paragraph Right (671):
This task 5324 is shown at the lower left-hand corner 0f the task diagram. When the vehicle is tracking, this task maintains the posture buffer (VPS.sub.-- POSTURE.sub.-- QUEUE) 5334. The task (5324) monitors the vehicle's position and maintains approximately 50 postures, from the current vehicle position in the direction of travel, in the posture buffer (3000).

Detailed Description Paragraph Right (672):
Shown in the upper right-hand corner of the task diagram FIG. 53, the task 5306 reads the current position 5332 and posture buffers 5334. Based on the information read, task 5306 calculates steer and speed corrections 420. It sends them to the vehicle 102, thereby controlling the vehicle's course.

Detailed Description Paragraph Right (697):
For example, when the executive task 5316 leaves the executive decisions 5508, and first enters the act on state block 5510, it checks to see that the status is set such that the vehicle is ready for autonomous mode (for example--VPS is ready, vehicle is communicating properly, a proper route has been commanded, and the vehicle is ready for auto mode). See block 5802. If one or more of these conditions is not met, then the Exec returns to wait for another valid message. If all of these conditions are met, then the executive 5316 checks to see that the path generator 5804 is operating. If so, then the executive 5316 proceeds to start the other systems required for autonomous operation.

Detailed Description Paragraph Right (698):
If the path generation system is not operating, then the executive 5316 task sends the message `VPS.sub.-- POSTURE.sub.-- ENGAGE` to the Vps Posture Queue 5334, in order to start the path generator. The executive task will then return to the Pend on Exec Queue 5506, to wait for another directive so that proper operation of the vehicle 102 is ensured.

Detailed Description Paragraph Left (2):
where V is the speed of a vehicle and L should be between L.sub.m in=10 and L.sub.m ax=30. Tracking performance is improved with the varying look-ahead distance 3310 of the present invention.

Detailed Description Paragraph Center (3):
1. NAVSTAR GPS

Detailed Description Paragraph Center (5):
D. Vehicle Positioning System (VPS)

Detailed Description Paragraph Center (19):
IV. Navigation System

Detailed Description Paragraph Center (24):
b. Modeling A Vehicle Path

Detailed Description Paragraph Center (45):
d. VEHICLE-GROUND INTERACTION (VGI):

Detailed Description Paragraph Center (68):
E. VEHICLE CONTROLLING SYSTEMS

Detailed Description Paragraph Center (70):
2. VEHICLE MANAGER (modes)

Detailed Description Paragraph Type 0 (3):
III. Vehicle Positioning System

Detailed Description Paragraph Type 0 (4):
IV. Navigation System

Detailed Description Paragraph Type 0 (7):
II Vehicle Positioning System

Detailed Description Paragraph Type 0 (8):
502. Host commands & queries: Commands given by the host to the vehicle manager. These commands could be of several types:

Detailed Description Paragraph Type 0 (25):

These are commands given to the vehicle to control steering and speed. These commands are issued at the rate of 2-5 Hz.

Detailed Description Paragraph Type 0 (38):
m: vehicle mass

Detailed Description Paragraph Type 0 (39):
I: vehicle moment of inertia

Detailed Description Paragraph Type 0 (40):
.THETA.: vehicle heading

Detailed Description Paragraph Type 0 (42):
NEW.sub.-- ROUTE.sub.-- DIRECTIVE: set the route number for the vehicle to follow.

Detailed Description Paragraph Type 0 (43):
CHANGE.sub.-- SPEED DIRECTIVE: command a maximum possible speed for which the vehicle can traverse a particular part of the route.

Detailed Description Paragraph Type 0 (44):
VEH.sub.-- RESPONDING: the vehicle is responding to commands properly, set Navigator status flags to Healthy.

Detailed Description Paragraph Type 0 (45):
NO.sub.-- VEH.sub.-- RESPONSE: the vehicle is not responding to commands, stop the vehicle.

Detailed Description Paragraph Type 0 (46):
VEH.sub.-- CHECKSUM.sub.-- ERR: the vehicle is not receiving/sensing data correctly, stop the vehicle.

Detailed Description Paragraph Type 0 (47):
TELE, MANUAL, READY, or AUTO: set the mode of the vehicle IN THE PROPER ORDER.

Detailed Description Paragraph Type 0 (48):
VPS.sub.-- TIMOUT: VPS is not sending data, stop the vehicle.

Detailed Description Paragraph Type 0 (49):
VPS.sub.-- CHECKSUM.sub.-- ERROR: the VPS is sending garbled data, stop the vehicle.

Detailed Description Paragraph Type 0 (52):
VPS.sub.-- POSITION.sub.-- ALIGN: the VPS is initializing, do not move the vehicle.

Detailed Description Paragraph Type 0 (53):
END.sub.-- OF.sub.-- ROUTE: the vehicle is approaching the end of the current route, has been reached inform the host processing system.

Detailed Description Paragraph Type 0 (55):
SCAN.sub.-- ALL.sub.-- CLEAR: no objects have been detected in the vehicle path, continue normally.

Detailed Description Paragraph Type 0 (56):
SCAN.sub.-- OBSTACLE: an object has been detected on the vehicle path, stop the vehicle.

Detailed Description Paragraph Type 0 (57):
TRACKER.sub.-- OFF.sub.-- COURSE: the vehicle is not following the desired path within tolerance, stop the vehicle.

Detailed Description Paragraph Type 0 (58):
TRACKER.sub.-- END.sub.-- OF.sub.-- ROUTE: tracker has reached the end of the path, stop the vehicle.

Detailed Description Paragraph Type 0 (59):
TRACKER.sub.-- STOPPED: notify the Navigator that the tracking task has stopped the

vehicle.

Detailed Description Paragraph Type 1 (1):
A. Vehicle Positioning System (VPS)

Detailed Description Paragraph Type 1 (2):
B. Navigation System

Detailed Description Paragraph Type 1 (5):
B. GPS Processing System

Detailed Description Paragraph Type 1 (19):
E. Vehicle Controlling Systems

Detailed Description Paragraph Type 1 (27):
where x and y represent the global position of the vehicle; O is the heading 3318 of the vehicle, and O is the rate of change of heading.

Detailed Description Paragraph Type 1 (30):
road height: the height of the road centerline above a reference plane described by the location of the four tires of the vehicle 102.

Detailed Description Paragraph Type 1 (34):
1. Project the vehicle path into the image plane 3901,

Detailed Description Paragraph Type 1 (42):
2. The navigation methods only have access to the local environment information in the form of a local map representing all of the visible faces of the obstacle from the position of the vehicle 102, which can be obtained from unprocessed laser range data or from data processed through blob-extraction;

Detailed Description Paragraph Type 1 (43):
3. The vehicle 102 is a conventionally steered type which has constraints on its speed and acceleration and constraints on its steering angle and the rate of change in the steering angle.

Detailed Description Paragraph Type 2 (1):
1. NAVSTAR GPS

Detailed Description Paragraph Type 2 (17):
2. Vehicle Manager (modes)

Detailed Description Paragraph Type 3 (6):
b. Modeling A Vehicle Path

Detailed Description Paragraph Type 3 (17):
d. Vehicle-Ground Interaction (VGI)

Detailed Description Paragraph Table (3):
e. VPS SHORT DEFINITION
Time: gps time North: wgs 84.sub.-- northing East: wgs 84.sub.-- easting Heading: compass direction vehicle is moving Curvature: calculated from other variable N.sub.-- velocity: north velocity E.sub.-- velocity: east velocity Yaw rate: rate of change of the heading G.sub.-- speed: ground speed distance travelled

CLAIMS:

1. A method for improving the accuracy of terrestrial position estimates of a user antenna located on a vehicle based on pseudoranges derived from satellites of a global position system, the method comprising the steps of:

(1) obtaining a known position of a reference antenna;

(2) receiving electromagnetic signals at said reference antenna from a constellation

of satellites and responsively determining respective reference antenna pseudoranges;

(3) determining an estimated position of said reference antenna using said reference antenna pseudoranges;

(4) comparing said estimated position of said reference antenna with said known position of said reference antenna to derive a spatial bias;

(5) transmitting said reference antenna pseudoranges and said spatial bias to the vehicle;

(6) receiving electromagnetic signals at the user antenna on the vehicle, receiving said reference antenna pseudoranges and said spatial bias at the vehicle and responsively determining a position estimate of the vehicle as a function of said spatial bias and said electromagnetic signals;

(7) at the vehicle, determining another estimate of the position of the reference antenna as a function of said reference antenna pseudoranges;

(8) determining an offset as a function of said another estimate of the position of said reference antenna and said known position of said reference antenna; and

(9) updating said position estimate of the vehicle as a function of said offset; and

(10) repeating steps (7)-(9) until said offset is less than a predetermined threshold.

2. A method for improvingthe accuracy of terrestrial position estimates of a user antenna located at a vehicle, the method comprising the steps of:

(1) obtaining a known position of a reference antenna;

(2) receiving electromagnetic signals at said reference antenna from a constellation of satellites and responsively determining respective reference antenna pseudoranges;

(3) computing an estimated position of said reference antenna using said reference antenna pseudoranges;

(4) comparing said estimated position of said reference antenna with said known position of said reference antenna to derive a base residuals bias;

(5) transmitting said base residuals bias and said reference antenna pseudoranges to the vehicle;

(6) receiving electromagnetic signals at the user antenna, receiving said base residuals bias and said reference antenna pseudoranges at the vehicle, and computing future user pseudoranges as a function of said base residuals bias;

(7) determining a position estimate of the vehicle as a function of said future user pseudoranges;

(8) at the vehicle, determining another estimate of the position of the reference antenna as a function of the reference antenna pseudoranges;

(9) determining an offset as a function of said another estimate of the position of the reference antenna and said known position of said reference antenna;

(10) updating said position estimate of the vehicle as a function of said offset; and

(11) repeating steps (8)-(10) until said offset is less than a predetermined threshold.

3. A method for estimating the terrestrial position of a vehicle (102), comprising:

(1) receiving electromagnetic signals at a base station from a constellation of

satellites and responsively determining a base spatial bias, a base clock bias, and base pseudoranges;

(2) transmitting said base spatial bias, said base clock bias, and said base pseudoranges to the vehicle;

(3) receiving electromagnetic signals at the vehicle from said constellation of satellites and responsively determining vehicle pseudoranges;

(4) receiving said base spatial bias and said base clock bias at the vehicle and determining a position estimate of the vehicle as a function of said base spatial bias, said base clock bias, and said vehicle pseudoranges;

(5) determining an estimate of the position of said base station at the vehicle as a function of said base pseudoranges;

(6) determining an offset as a function of said estimate of the position of said base station and a known position of said base station;

(7) updating said position estimate of the vehicle as a function of said offset; and

(8) repeating steps (5)-(7) until said offset is less than a predetermined threshold.